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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

7 RUE ANCELLE 92200 NEUILLY SUR SEINE FRANCE

AGARD REPORT 773

AGARD/SMP Review
Damage Tolerance for Engine Structures
4. Reliability and Quality Assurance

(Revue AGARD/SMP — Tolérance aux Dommages pour les Composants de Moteurs
4. Fiabilité et Assurance Qualité)

Papers presented at the 69th Meeting of the AGARD Structures and Materials Panel, held in Brussels, Belgium 1st—6th October 1989.

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North Atlantic Treaty Organization
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Preface

Most current military and all civil engines are operated under "Safe-life" procedures for their critical components. Experience has shown that this philosophy presents two drawbacks:

(a) The move towards designs allowing higher operational stresses, and the use of advanced high-strength alloys make it likely that a disc burst could happen (following a rapid crack growth) well before the statistically-based "Safe-life" has been achieved.

(b) It is potentially wasteful of expensive components, since it has been estimated that over 80% of engine discs have ten or more low cycle fatigue lives remaining when discarded under "Safe-life" rules.

Damage Tolerance being an alternative lifeing philosophy, the Sub-Committee on "Damage Tolerance Concepts for the Design of Engine Constituents" has therefore decided to conduct a series of four Workshops addressing the areas critical to Damage Tolerant design of engine parts.

The present report includes the papers presented during Workshop 4 which was devoted to Reliability and Quality Assurance.

It also includes the content of the discussions which followed the presentations. On behalf of the Structures and Materials Panel, I would like to thank the authors, the recorders of the discussions and the session chairmen whose participation has contributed so greatly to the success of the Workshop.

Préface

La totalité des moteurs civils et la plupart des moteurs militaires sont actuellement mis en oeuvre suivant les concepts de "durée de vie certaine" en ce qui concerne leurs parties vitales. La pratique de cette approche a mis en évidence les deux inconvénients suivants:

(a) La tendance à l'utilisation des moteurs sous contraintes mécaniques plus élevées et l'emploi d'alliages à haute résistance rendent possible l'éclatement d'un disque (à la suite d'une progression rapide de fissure) avant que la "durée de vie certaine", évaluée statistiquement, ait été atteinte.

(b) On observe également un gaspillage de pièces onéreuses, puisqu'on estime que 80% environ des disques retirés du service conformément aux règles de "durée de vie certaine" ont encore un potentiel supérieur à dix durées de vie en fatigue oligocyclique.

La Tolérance aux Dommages constituant une autre approche possible de la définition des potentiels de vie, le Sous-Comité "Concepts de Tolérance aux Dommages pour le dimensionnement des composants de moteurs" a décidé d'organiser une série de quatre Ateliers consacrés aux divers aspects de la Tolérance aux Dommages appliquée aux moteurs.

Le présent rapport contient les diverses présentations effectuées à l'occasion du dernier d'entr'eux traitant de la Fiabilité et de l'Assurance Qualité. On y trouve également un compte-rendu des discussions qui ont suivi les diverses présentations.

Au nom de la Commission Structures et Matériaux, je remercie les auteurs, les rapporteurs de discussion et les présidents de sessions qui ont grandement contribué au succès de cet Atelier.

R. Labourdette
Chairman, Sub-Committee on
Damage Tolerance Concepts
for the Design of Engine
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INTRODUCTION - NEEDS AND APPROACHES TO RELIABILITY AND QUALITY ASSURANCE IN DESIGN AND MANUFACTURE

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INTRODUCTION

An AGARD meeting on the Damage Tolerance Concept (DTC) was held in San Antonio in 1985. One of the conclusions of this meeting was that DTC offers a way to improve the integrity and efficient utilisation of critical aero engine components, in particular those manufactured from the high strength materials which are required to meet the design objectives set for high performance military engines. Following this meeting, a series of workshops were arranged to investigate various aspects of DTC.

The fourth workshop meeting is aimed at exploring reliability and quality assurance issues in the Damage Tolerance approach. To this end, a series of papers are to be given, following this introduction, to explore the implications on DTC of:

(a) Component material specifications and standards.

(b) Controls on manufacturing processes and procedures.

(c) Design systems and quality assurance.

The meeting will also explore the possibility of a common AGARD approach and Database on quality - and integrity-related issues which arise during aero engine component life assessment.

The Need for Quality Assurance

The primary goal for Quality Assurance is to provide Customer Satisfaction. From the customer's viewpoint, this means that the product must meet the specification. This is not the complete story, however; there must also be good communication between the customer and the manufacturer. The aim here is to ensure that the customer gives a clear, unambiguous specification of what is required and that the manufacturer understands all aspects of this.

A good example of this is the definition of the mission profiles, mission mixes and life requirements which the aero engine is designed to achieve. A simple requirement that "the engine fracture critical parts must achieve an inspection interval of x hours" is an insufficient definition, since the relationship between cyclic life usage and time in service depends on the types of mission flown. Equally, if the customer defines mission

profiles and mission mixes and then uses the engine for different profiles or mixes, he must expect to see a consequent change in the lives achieved expressed in hours and/or cycles. In the case of cyclic life-limited components, however, the life in "equivalent cycles" should not change in these circumstances.

Formality and Audit

Quality can be considered as a "state of mind" which should pervade all levels of a design/manufacturing organisation; it is necessary that companies have the correct infrastructure to encourage a "quality" approach. Two important aspects of this are:

(a) Formal systems must be implemented covering all aspects of the product definition and manufacturing processes.

(b) Regular review and audit must be performed against the formal system requirements, both internally (self-audit) and externally (customer audits). There must also be an acceptance of the need to change a system if an audit reveals a potential quality problem.

Audit is the means by which the customer can check that the supplier will deliver products of the required level of quality. This approach should pervade the design/manufacturing organisation - every interface within the Company can be thought of in terms of "customer/supplier" relationships.

Definition of Accountability

Definition of accountability is important, both within the design/manufacturing organisation and between this and the customer. From a supplier viewpoint, it is necessary to ensure consistency and formality of approach and to avoid duplication/ overlap or gaps in the overall product definition/manufacture process. Smooth operation of interfaces is a key requirement for efficiency and quality. From a customer viewpoint, it is necessary to know the limits of accountability of the supplier and activities for which the customer is responsible - for example, the definition of missions and mission mixes. It is also important that the customer should have identified contact points within the Supplier organisation from which advice can be sought and rapid resolution of problems obtained.

Quality Assurance in Design

Verification is a key issue in the assurance of quality in Design. The methods used in the design process must be correlated against observed behaviour; this may be accomplished by performing measurements using instrumented development engines, or by appropriate rig testing. The validated design methods must then be embedded in appropriate procedures to ensure their correct use and to call up direct verification tests where necessary.

Examples of information required for direct design verification are:

(a) Performance checks and measurements.

(b) Secondary air system measurements (flows, pressure ratios, air temperatures).

(c) Metal temperature measurements.

(d) Vibratory stress measurements.

(e) Development engine growth measurements.

(f) Damage tolerance crack growth measurements in cyclic engine tests.

Indirect verification is usually performed for:

(a) Stress analysis methods, using instrumented rig tests.

(b) Component overspeed capability, using rig tests.

(c) Component cyclic life capability, using rig tests combined with laboratory specimen tests, to give an understanding of materials behaviour.

Figure 1 shows a summary of the procedures, methods, verification tests and service life management approach required for critical component design, life estimation, validation and management.

Past experience clearly plays a large part in ensuring a "quality" design is produced. The incorporation of this experience and derived Design criteria into appropriate databanks is important; easy access to this information during the design process ensures that good past design practice is fed into new designs.

Component and Material Specifications and Standards

Accurate specification of the materials used in gas turbines is essential in ensuring a "quality" design. Table 1 indicates some of the key quality standards which need to be specified to ensure that the material behaviour will match the design intent. While some of these may be monitored for each component by specification of appropriate material release properties, others are dependent on sampling programmes and the definition of appropriate standardisation and approval materials evaluation packages.

One key question here is "is the specification absolute, or is it relative to some process?". A good example is the definition of inspection requirements, which may be absolute (e.g. No cracks bigger than x mm long are acceptable) or relative to the inspection process (e.g. No cracks visible when viewed with x3 binoculars under some standard conditions, with standard eyesight inspectors).

Quality Assurance in Production

Control of the manufacturing process is essential to both the traditional "safe life" and Damage Tolerance approaches to component life management. Lack of manufacturing process control can lead to unacceptable levels of scatter in component behaviour and the risk that the parameters used to establish minimum component life (e.g. results of individual rig tests) may not be representative of the complete family of components in service.

Key issues here are:

(a) Definition of manufacturing methods.

(b) Fixed practice concepts.

(c) Relationship of process control to design intent.

(d) Statistical process control as a means of monitoring process variability.

(e) Change procedures.

(f) Non conformance and accept/reject criteria.

(g) Process control and inspection criteria.

While the need for quantification of process control methods is recognised, a key question is "what validation evidence is required to demonstrate the achievement of process control?". Development of process modelling methods is expected to assist in the identification and control of key process variables in support of a quantitative approach to this issue.

The Workshop

The aim of this workshop on reliability and quality assurance is to investigate some of the issues raised in this introduction, and to review:

(a) The need for a common AGARD approach to:

- material and process specifications
- lifing standards
- hazard analysis
- in service life monitoring
- information exchange

(b) The possibility of constructing an AGARD database on integrity related issues:

- materials behaviour (defect types, etc)
- effects of damage
- environmental effects
- mission related behaviour

TABLE 1

FACTORS IN ENGINEERING QUALITY STANDARDS

Surface Requirements

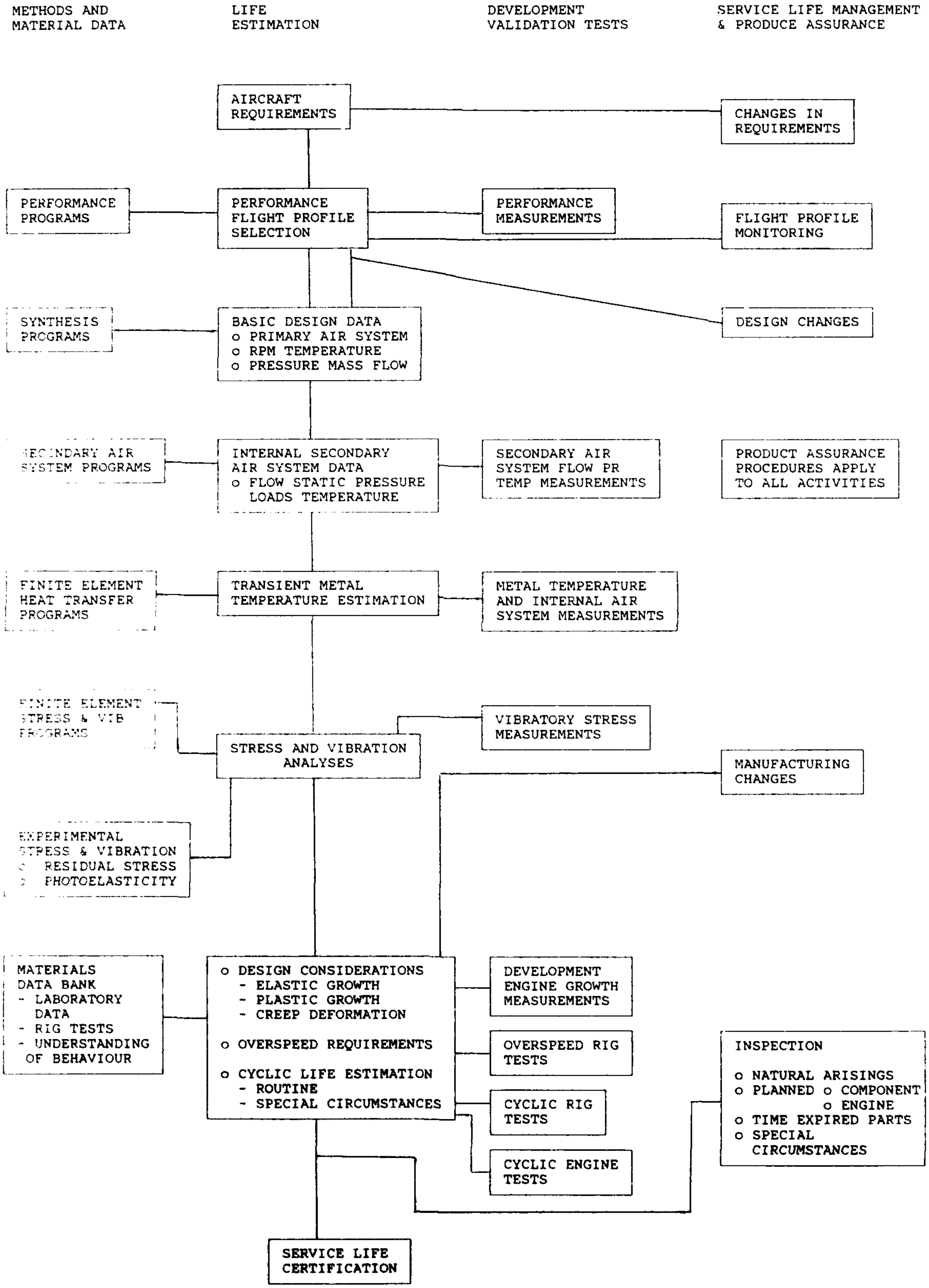
- o Permitted Crack Size (mm)
- o Grain Size (mm)
- o Macrostructural features (mm)
- o Microstructural features (mm)
- o Inclusions (mm)
- o Porosity (mm)
- o Machinery abuse/Surface strain
- o Scratches (mm)
- o Dents/Bruising

Sub-Surface Requirements

- o Ultrasonic Response as standard Artificial Defect (SAD) - equivalent flat bottom hole size
- o Inclusion Size
- o Residual Stress
- o Defect distribution (within component and on going)
- o Microstucture

LIFE ESTIMATION, VALIDATION AND MANAGEMENT

FIG. 1



LA MAITRISE DES PROCEDES DE FABRICATION DANS UNE CONCEPTION DE TOLERANCE AUX DOMMAGES

par

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Concevoir un produit "Tolérant aux Dommages" consiste à considérer qu'il peut contenir des dommages ou défauts, déterminer les caractéristiques de ces dommages et défauts et faire en sorte qu'ils n'évoluent pas, pendant la durée d'utilisation considérée, d'une façon telle que l'intégrité structurale du produit ne soit plus assurée. Les défauts initiaux que génère le processus de fabrication font bien évidemment partie des dommages à prendre en considération.

La maitrise des procédés de fabrication est la constante recherche de la plus basse variabilité possible des caractéristiques des pièces produites. Il s'agit bien, en jouant sur tous les plans possibles (méthodes, moyens, hommes, etc...) de tendre vers l'absence de "défauts", quel que soit le sens que l'on puisse donner au terme. A première vue, mais à première vue seulement, il pourrait sembler paradoxal de traiter de la place de la maîtrise des procédés dans la conception et production de produits Tolérants aux Dommages : si, pourraient estimer certains, les défauts sont tolérables, pourquoi ne pas en tirer parti en allégeant les efforts visant à les supprimer et, par là même, obtenir une réduction des coûts de production ?

Une telle stratégie est a priori dangereuse, car le postulat sur lequel elle se fonde n'est en pratique guère vérifié par l'expérience industrielle. Augmenter la variabilité d'un procédé diminue rarement les coûts de production, mais comporte au contraire bien des germes de surcoûts considérables : nécessité d'introduire des inspections supplémentaires, accroîssement des analyses pour sanctionner les non--conformités, augmentation des retouches et rebuts, le tout générant une dégradation importante des cycles et valeurs d'exploitation.

Mais cette stratégie de "moindre maîtrise des procédés" constituerait aussi et surtout une faute susceptible de mettre en péril la qualité même du produit conçu Tolérant aux Dommages. La maîtrise des procédés est autant, sinon davantage, nécessaire dans une conception de Tolérance aux Dommages que dans une conception conventionnelle de "Vie Sûre". Ceci pour des raisons qui tiennent d'une part à la fiabilité et sûreté d'exploitation du moteur et d'autre part à son coût global de possession. Nous passerons en revue ces raisons dans la première partie de l'exposé.

Par ailleurs, la Tolérance aux Dommages contient en elle-même un certain nombre de concepts qui peuvent être utilisés avec profit pour modifier, infléchir et améliorer les modalités d'accession à cette nécessaire maîtrise des procédés. Nous en examinerons quelques uns dans la seconde partie de l'exposé.

NECESSITE DE LA MAITRISE DES PROCEDES

Fiabilité et sûreté de fonctionnement : défauts ponctuels.

Considérons tout d'abord les défauts métallurgiques à caractère ponctuel ou local, tels que fissures de rectification, de soudure, de traitement thermique, repli ou déchirure de forge, micro-retassures ou soufflures de fonderie, inclusions ou ségrégations provenant de l'élaboration, etc... Après une éventuelle période "d'incubation", très variable et imparfaitement prévisible en l'état actuel des modélisations, toutes ces discontinuités locales du matériau sont susceptibles de se developper en utilisation, en suivant peu ou prou les lois de la mécanique de la rupture. Et, toutes choses égales par ailleurs, ces lois sont telles que la durée de vie résiduelle d'une pièce est extrêmement sensible à la dimension de la fissure - ou quasi fissure - initiale considérée. Une incertitude de quelques dixièmes de mm sur cette dimension initiale peut conduire à une erreur de 50 % à 100 % sur le nombre de cycles de propagation avant la rupture brutale. L'intégrité structurale d'une pièce Tolérante aux Dommages dérive donc de la précision et de la fiabilité de la détermination des caractéristiques de la fissure ou défaut initial. D'une façon générale, cette détermination fait appel à un contrôle non destructif, pratiqué systématiquement pendant le cycle de fabrication, puis repété, si nécessaire, périodiquement au cours de la vie de la pièce. La taille du défaut initial, dont on doit assurer une propagation sub-critique, pendant la période considérée est alors celle correspondant aux taux de probabilité de détection et de confiance qui sont estimés nécessaires et suffisants (par exemple 99 % - 95 %).

.../...

Les méthodes qui permettent d'obtenir ces données statistiques sont de mise en oeuvre lourde et délicate, et les résultats, en termes de défaut minimum détectable, parfois éloignés des souhaits du concepteur. L'ensemble a largement été discuté au cours de la première session de l'atelier AGARD - SMP, consacrée aux méthodes d'inspection non destructive, et nous n'y reviendrons pas ici. Force est cependant de constater que la fiabilité de l'inspection, si elle est essentielle dans une conception Tolérante aux Dommages, n'est pas toujours suffisante à elle seule. Il est souvent nécessaire de lui associer, et quelquefois, de lui substituer, la fiabilité de fabrication, c'est à dire de combiner le risque de non-détection du défaut et le taux d'occurence de ce dernier.

Bien des défauts métallurgiques cités plus haut sont dans une situation où une combinaison de ce type est nécessaire. En effet, dans le meilleur des cas, seules sont accessibles et connues, des probabilités de détection exprimées en terme d'étalons de référence (diamètre du reflecteur à trou à fond plat en contrôle ultra sons, surface d'une entaille usinée en contrôle par courants de Foucault, IQI en contrôle radiographique, etc...). Or il n'existe pas toujours de corrélation simple ou systématique entre ces grandeurs de référence et les caractéristiques physiques du défaut métallurgique, qui déterminent la durée de vie résiduelle réelle de la pièce.

Le cas des disques de compresseur ou turbine haute pression élaborés par métallurgie des poudres constitue un bon exemple de cette nécessaire complémentarité entre inspection et maîtrise du procédé. Ces produits contiennent en effet des inclusions de natures diverses (céramiques provenant du four de fusion, de la busette d'atomisation, etc...), dont la distribution est liée à la dimension du tamis choisi et la technologie de l'ensemble du procédé. L'objectif, pour un moteur militaire d'une durée de vie résiduelle en propagation de quelques milliers de cycles correspond à des dimensions maximales d'inclusion variant entre 100 et 500 microns environ, selon le niveau de contrainte, la température, le type et les zones de pièce, et la nature physique de l'inclusion. Au prix de developpements technologiques et d'investissements importants, et d'un coût d'inspection considérable, il est possible, par ultra-sons (dans le volume) et courants de Foucault (en surface), de garantir la détection de "défauts parfaits" (trou à fond plat, etc...) dont les dimensions correspondent aux 100 à 500 microns recherchés. Mais, comme le montre la figure 1, la taille du "défaut parfait équivalent" (diamètre du trou à fond plat), telle qu'estimée d'après l'inspection ultrasonore par exemple, n'est que faiblement corrélée avec les dimensions exactes de l'inclusion correspondante (mesurée par dissection de l'indication U-S). Dans une situation de ce genre, l'assurance que la durée de vie résiduelle (DR) est bien celle prévue repose sur une double assertion du type :

1°) Probabilité $\geqslant$ 99 %, confiance $\geqslant$ 95 % de détecter une fissure initiale dont la vie en propagation est *DR*.

2°) Probabilité $\leqslant 10^{-4}$ qu'une pièce possède une inclusion dont la vie en propagation est *DR*.

Bien entendu en supposant même que l'assertion 1 puisse être suffisante à elle seule, un procédé peu maîtrisé , qui s'éloignerait beaucoup de l'assertion 2, n'aurait aucune viabilité économique, car il gènèrerait des rebuts exhorbitants lors des inspections. Pour piloter l'accession à la maîtrise du procédé de métallurgie des poudres, l'on dispose d'un certain nombre d'indicateurs qui permettent de mesurer la distribution - ou plutôt une partie de celle-ci - des inclusions tout au cours de l'élaboration : élutriation et dissolution acide des poudres, micrographie des billettes, refusion de "boutons" par bombardements d'électrons. La figure 2 montre comment des actions volontaires (modifications d'équipement, etc...) mais aussi des évènements "extérieurs" (comme une interruption puis reprise de la production) se répercutent effectivement sur de tels indicateurs. Et la figure 3 confirme qu'il existe bien une certaine corrélation entre ces mesures revélatrices en amont de la meitrise du procédé, et le taux de défaillance lors de l'inspection finale.

Les inclusions inhérentes au procédé de métallurgie des poudres ne doivent pas être considérées comme un cas isolé ou très particulier. Les ségrégations alphagènes dures, à base d'interstitiels (O,N,C) dans les alliages de titane, les ségrégations de carbonitrures complexes (white-spots) dans les alliages de Nickel élaborés VIM/VAR soulèvent des questions voisines et appellent des solutions analogues. Simplement les conditions de sollicitation des pièces (température, contraintes) sont en général moins sévères, les défauts "tolérables" plus importants. Ils ne sont pas pour autant toujours facilement inspectables et maîtrisables aux niveaux nécessaires.

<u>Fiabilité et sûreté de fonctionnement</u> : <u>défauts non ponctuels</u>.

Si les défauts ponctuels, proches d'une fissure, sont les premiers qui viennent à l'esprit lorsque l'on traite de la Tolérance aux Dommages, ils ne sont pas les seuls à devoir mériter l'attention. D'autres défauts, plus globaux, tels que les écarts dimensionnels ou des variations de microstructure métallurgique peuvent ruiner la fiabilité d'une conception Tolérante aux Dommages si celle-ci ne les incorpore pas.

.../...

Des non-conformités dimensionnelles peuvent générer des perturbations aérodynamiques, modifier les conditions aux limites, les fréquences propres et les amortissements, amoindrir les marges vis à vis des flottements aéroélastiques avec comme conséquence possible, l'apparition d'une composante vibratoire se superposant à la sollicitation oligocyclique. Or l'influence des sollicitations vibratoires sur la propagation des fissures est particulièrement forte. Une composante vibratoire atteignant simplement 15 % de la sollicitation oligocyclique sera le plus souvent sans grand effet sur la durée de vie à l'amorçage. Mais il suffira qu'elle soit rencontrée quelques dizaines de secondes seulement par vol, à une fréquence de l'ordre de la centaine d'Hertz, pour que les durées de vie en propagation, exprimées en nombres ou en heures de vol, soient divisées par un facteur égal ou supérieur à 5. Aucun coefficient de sécurité sur les intervalles d'inspection ne saurait couvrir une telle variabilité ; c'est bien à la maîtrise des procédés de fournir l'assurance que si ce type de phénomène n'a pas été rencontré pendant le développement et la certification du moteur, il ne se rencontrera pas non plus sur les moteurs de production.

Le cas des variations de microstructure métallurgique est légèrement différent. Là aussi, les liens entre la microstructure (taille et morphologie des grains, des phases durcissantes, etc...) et les vitesses de fissuration sont forts, même s'ils sont souvent complexes et dépendent, entre autres, de la taille de fissure et des conditions de sollicitation considérées. Mais une difficulté supplémentaire apparait : dans la plupart des cas en effet, les variations de microstructure ont aussi une influence importante sur les durées de vie à l'amorçage, et cette influence est généralement de signe opposé à celle portant sur les durées de propagation. La dispersion des microstructures est alors doublement néfaste il ne saurait être question en effet d'assurer la sûreté d'exploitation de la pièce au détriment de sa vie économique. La première est fondée sur des calculs de propagation, qui seront vérifiés si la taille de grain est "suffisamment" grande. Mais un grain "trop" gros dégradera la seconde. L'introduction du concept de Tolérance aux Dommages, dans cet exemple, se traduit donc par une nécessité accrue de maitriser les variations de taille de grain.

Nous avons jusqu'à présent traité de "défauts" au sens le plus habituel du terme, c'est à dire de violations des spécifications constituant la définition du produit. Et il est apparu clairement que l'intégrité structurale des pièces conçues Tolérantes aux Dommages ne peut être assurée par la seule inspection des "défauts". La maîtrise des procédés est bien à cet égard un complément indispensable des inspections et la seule voie permettant d'aboutir à une garantie suffisante que les pièces ne comporteront effectivement pas de "défauts non tolérables". Mais la maîtrise des procédés ne se borne pas à offrir cette assurance de capabilité de vis à vis des spécifications ; elle vise aussi à réduire la variabilité des produits à l'intérieur de la plage de tolérance. Et ceci est également d'une grande utilité pour des pièces Tolérantes aux Dommages, pour des raisons qui constituent en quelque sorte une généralisation de l'exemple des microstructures traité ci-dessus.

La maîtrise du coût global de possession

La dispersion des caractéristiques (de toutes natures : métallurgiques, dimensionnelles, de surface, etc...) des pièces est, avec celle des conditions d'utilisation du moteur, directement à l'origine de la dispersion des durées de vie à l'amorçage et en propagation qui serait observée si les moteurs étaient exploités de façon "absolue". Dans une conception conventionnelle de "Vie Sûre", beaucoup de pièces tournantes critiques (disques, arbres) ont une Durée de Vie Autorisée, obtenue par application d'un facteur de sécurité à la Durée de Vie Prévue (par calcul et essais) de la pièce de caractéristiques minimales. Les liens entre maîtrise des procédés et coût global de possession existent donc, mais de façon partielle et parfois saturée dans la mesure où il est difficile de traduire, au cours de la vie d'un programme, une réduction de variabilité des caratéristiques produites en terme d'accroissement des Durées de Vie Prévues ou de diminution de facteur de sécurité. A l'inverse, une pièce insuffisamment maîtrisée, dont la durée de vie réelle serait inférieure à la Durée de Vie Prévue, pourra ne poser aucune difficulté tant que le facteur, de sécurité masquera son insuffisance, puis entrainer une situation catastrophique si la Durée de Vie Autorisée venait elle-même à plus être assurée.

Dans une approche de Tolérance aux Dommages, les liens entre maîtrise des procédés et coût global de possession deviennent à la fois plus directs et plus continus. Exploitée dans son intégralité (Retirement for Cause), cette conception peut aller jusqu'à autoriser le maintien en service sans autre limite que leur durée de vie (à la détection du Dommage maximum Tolérable) réelle. Dans une telle situation, toute dispersion de caractéristiques se répercutera directement sur les durées d'utilisation effectives des pièces ; une dispersion excessive, occasionnant un nombre imprévu et élevé de déposes "prématurées" conduirait à des conséquences extrêmement lourdes sur le plan logistique. Il faudrait ou bien accepter le risque d'indisponibilités opérationnelles, ou bien se couvrir par la constitution de volants de pièces de rechanges considérables : le bénéfice que l'on peut attendre du concept Tolérance aux Dommages/Retirement for Cause se trouverait annulé, voire transformé en surcoût global de possesion.

.../...

La conception Tolérance aux Dommages requiert donc, cette fois sur un plan purement économique, que l'on cherche à diminuer autant que possible les "petits défauts (tolérables initialement) susceptibles de devenir grands". les seuils de non propagation intrinsèques étant plutôt bas, ceci se traduit par une chasse constante aux rayures et blessures de manutention, écarts de forme sur un congé de raccordement, bourrelets en limite de zone grenaillée, etc... On trouvera, si besoin, aux figures 4 et 5, des exemples de fissures de fatigue amorçées, en essais partiels, sur des "défauts" de ce genre. Leur élimination totale est certes malaisée. Mais des progrès significatifs peuvent être réalisés dès lors que leur nécéssité est bien comprise. La figure 6 montre comment l'on peut avancer dans la maitrise des formes des congés de raccordement des festonnages et alvéoles de disques de turbine basse pression. Une première amélioration importante a été obtenue par la mise en place d'un contrôle intégré permettant au compagnon de contrôler lui-même la qualité du rayonnage, et donc de réagir "en temps quasi-réel". Une seconde étape d'amélioration paraît se dessiner avec l'automatisation de l'opération de rayonnage, qui apporte un meilleur potentiel de répétabilité (fig. 7). Un autre exemple est fourni fig.8, où la mise en place de conditionnements adaptés aux disques de turbine a permis d'améliorer sensiblement leur état de surface et le nombre de retouches nécessaires suite à des chocs et blessures de manutention.

APPORTS DE LA TOLERANCE AUX DOMMAGES A LA MAITRISE DES PROCEDES

La maîtrise des procédés est, nous l'avons vu hautement nécessaire dans une approche de Tolérance aux Dommages. Bien entendu les outils habituels d'accession à cette maitrise s'appliquent parfaitement :

- Surveillance statistique des produits, processus et moyens.
- Maintenance préventive, analyse de fiabilité des moyens.
- Groupes d'action Qualité.
- Modélisation des procédés.
- etc...

Mais le concept de Tolérance aux Dommages permet sans doute d'aborder sous un angle nouveau et prometteur le classique problème de la "négociation" entre exigences de conception (spécification) et capacités des procédés.

Voici à titre d'exemple, la démarche qui a été suivie pour une aube de turbine HP monocristalline (alliage AM1), caractérisée par la finesse de ses parois, la sophistication de son refroidissement interne et une température élevée de fonctionnement (TET = 1850°K). A l'issue de la fabrication des 20 premiers jeux et de la première centaine d'heures d'essais de developpement, un groupe de travail multifonctionnel (Bureau d'Etudes - Méthodes et Atelier de fabrications - Qualité) a réalisé ce que l'on peut appeler une "revue du produit", selon la méthodologie suivante :

. 49 spécifications analysées, de toutes natures : métallurgiques, dimensionnelles, etc...

. 3 critères : - Criticité Fonctionnelle
- Capabilité du procédé de fabrication
- Fiabilité des contrôles de fabrication.

. 4 ou 5 niveaux de cotation :

- Pour la criticité fonctionnelle :

5- Effet sur la navigabilité.
4- Effet sur le coût de possession, les performances.
3- Autres effets.
2- Marge $\geqslant$ 50 %
1- Marge $\geqslant$ 100 %

- Pour la capabilité du procédé de fabrication et la fiabilité des inspections :

5- Procédé non capable - Inspection non fiable, innovations nécessaires
4- Marges de capabilité, probabilité de détection à améliorer
3- Variabilité à améliorer pour des raisons de coût
1- Procédé sous contrôle

Ces cotations sont effectuées, entre autres, à partir des enseignements du suivi statistique du procédé, taux de rebuts, retouches, histogrammes et cartes de contrôle, etc...

.../...

Dans un premier temps, chacune des 49 caractéristiques est reportée dans un diagramme Capabilité du procédé/Fiabilité d'inspection. Ce diagramme permet de détecter les points sur lesquels une action immédiate s'impose. Ensuite, ces 49 caractéristiques sont placées (fig.9) dans un diagramme Criticité fonctionnelle/Capabilité du procédé x Fiabilité du Contrôle, (d'autres combinaisons de ces 2 critères sont possibles). A l'issue de cette analyse, le groupe de travail a émis 55 propositions dont :

. 13 révisions de spécifications
. 26 modifications (dont 7 majeures, c'est à dire entrainant des investissements) des procédés de fabrication et de contrôle.
. 16 programmes d'essais partiels ou sur moteur destinés à vérifier, lorsque nécessaire, la caractère "Tolérable" de certaines variations.

Ce type de démarche consiste bien à assurer la Tolérance aux Défauts, et par son caractère universel fédère et coordonne les efforts de chacun dans le but commun et ultime de la satisfaction du client. Cette démarche peut naturellement être appliquée aussi avec grand profit dès les premiers stades de la conception (dessins initiaux), quitte à être réajustée au cours du développement, au fur et à mesure que l'expérience en production et en essai apporte des précisions sur les défauts spécifiques de la pièce considérée et leur comportement particulier sur le moteur en question.

Dans un esprit voisin, les concepts de Tolérance aux Dommages peuvent également fournir de nouvelles opportunités pour faire largement diffuser au sein de l'entreprise les liens qui existent entre la qualité du travail de chacun, et le comportement du produit en utilisation. Nous avons, par exemple, mis en place un stage de formation sur le thème "fatigue et mécanique de la rupture" destiné à un public aussi large que possible de techniciens et ingénieurs, provenant d'horizons les plus divers, équipes de marque ou de programme, laboratoires, services méthodes, encadrement d'ateliers, services techniques d'après-vente, etc..

D'une durée de 4 jours, ce stage comporte un enseignement théorique extrêmement rudimentaire sur les sollicitations dans les turbo-machines, les lois de la fatigue et de la mécanique de la rupture, mais aussi un aperçu statistique sur les origines des défaillances structurales des moteurs en service. Il comporte surtout plusieurs "études de cas", conçues à partir d'expertises réellement effectuées à l'occasion de ruptures survenues en exploitation, bien entendu simplifiées ou complétées pour les besoins de la cause. Pendant ces études de cas, les participants, en groupe, sont amenés à :

- Identifier et comprendre les causes initiales de la défaillance structurale.
- Vérifier, par des calculs très sommaires, les effets du défaut sur les durées de vie à l'amorçage et en propagation.
- Confronter ces calculs avec les données issues des examens fractographiques (stries, lignes d'arrêt, etc...).
- Proposer des procédures de maintien en exploitation, sous concept de Tolérance aux Dommages, de matériels qui présenteraient les mêmes causes potentielles de défaillance : choix des techniques de contrôle, des intervalles d'inspection, etc...
- d'Evaluer les conséquences logistiques de telles procédures auprès du client.

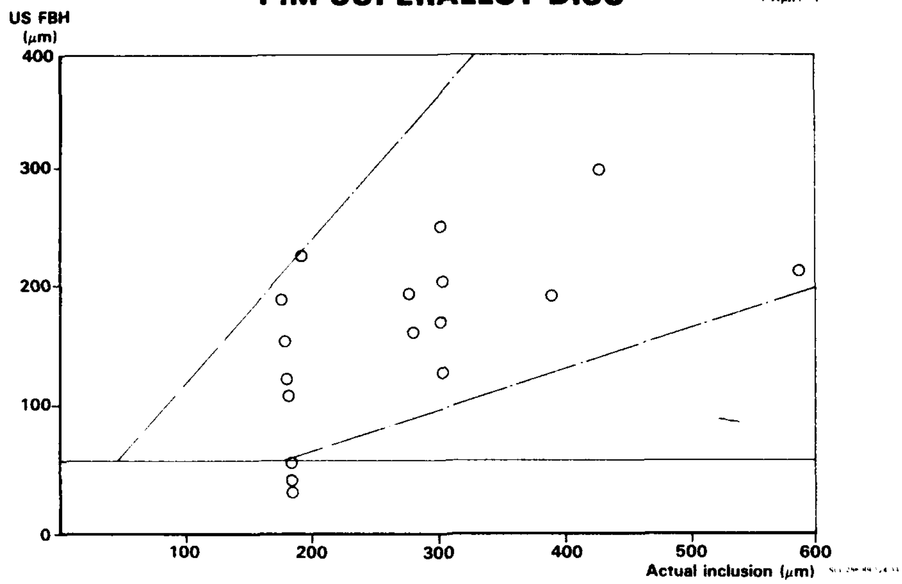
Les personnes ainsi formées ne deviennent pas pour autant des experts en Tolérance aux Dommages. Mais elles acquièrent une bien meilleure visibilité sur cet aspect des phénomènes et mécanismes qui se produisent en amont, en aval et au sein de leur travail de chaque jour. L'impact qu'elles ont sur la satisfaction du client final leur apparaît plus clair et plus proche. Davantage motivées, elles peuvent s'impliquer de façon plus approfondie et plus cohérente à l'intérieur du processus industriel global de conception/production/exploitation.

La Tolérance aux Dommages appliquée aux moteurs d'avions, se présente ainsi à la fois comme une "ardente obligation" supplémentaire de progresser dans la maîtrise des procédés et comme l'opportunité d'introduire des voies nouvelles pour accéder à cette maîtrise.

.../...

P.M SUPERALLOY DISC

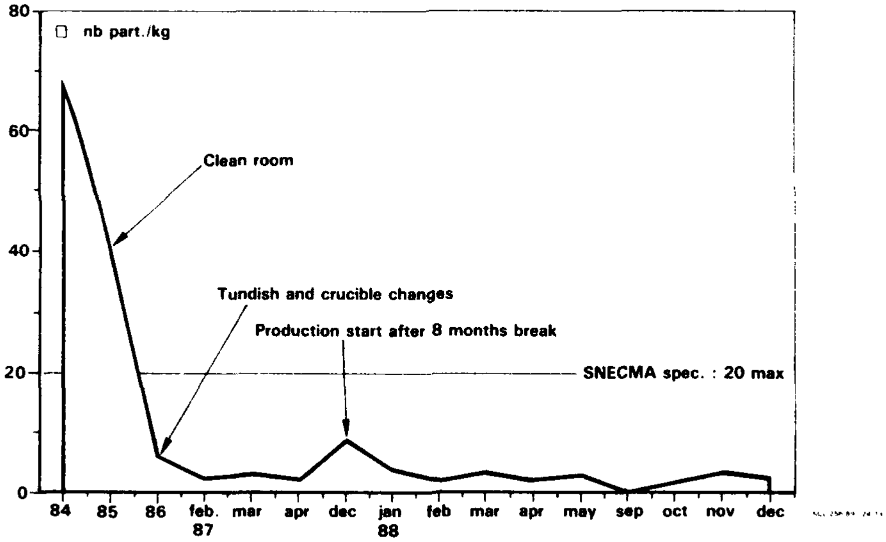
- Figure 1 -



P.M PROCESS CONTROL

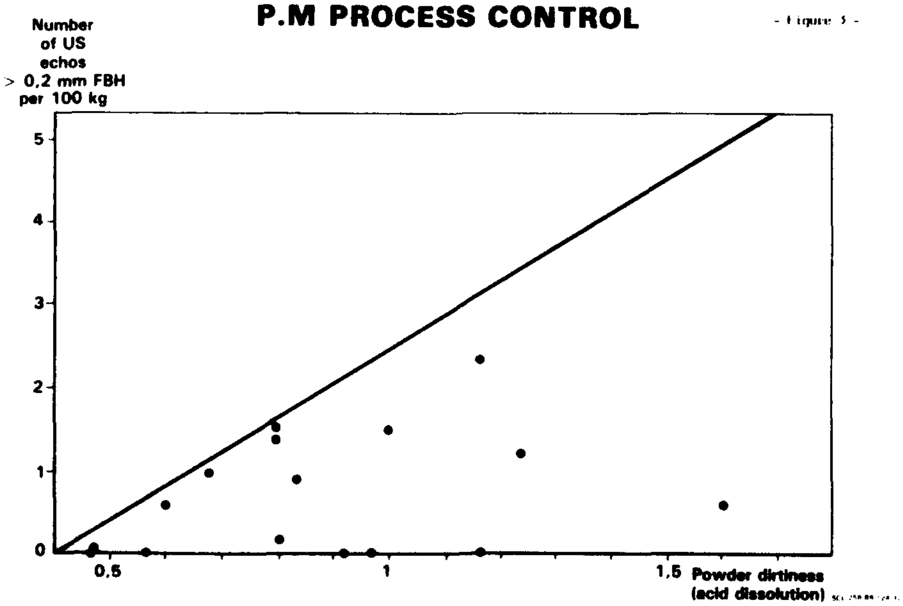
- Figure 2 -

CLEANLINESS FLOW CHART (ELUTRIATION)



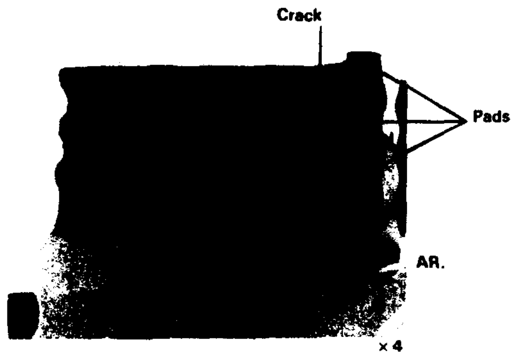
P.M PROCESS CONTROL

- Figure 3 -



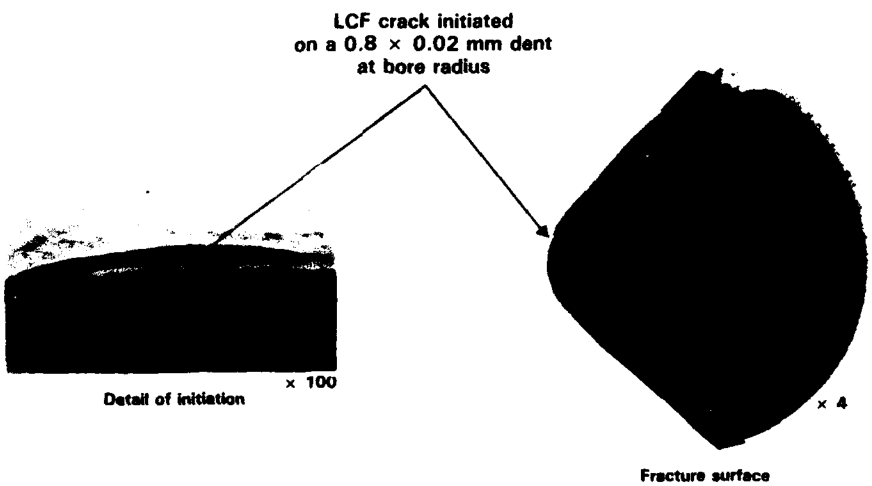
HPT DISC : LCF DOVETAIL CRACK INITIATION ON SHOT-PEENING PADS

- Figure 4 -



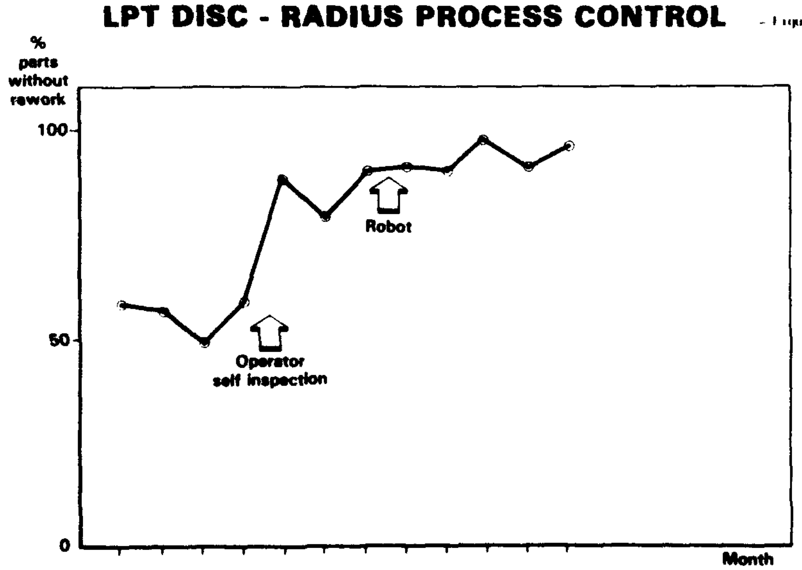
P.M HPT DISC

- Figure 5 -



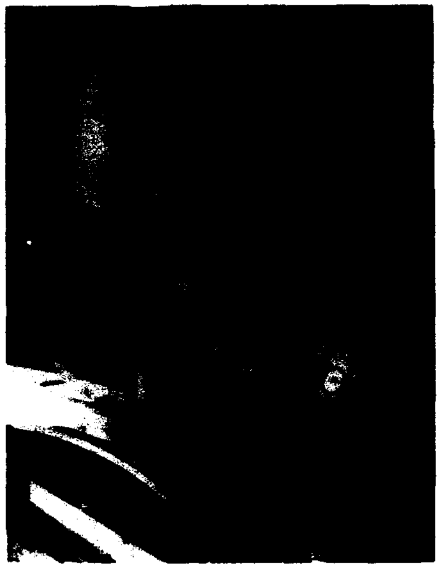
LPT DISC - RADIUS PROCESS CONTROL

- Figure 6 -



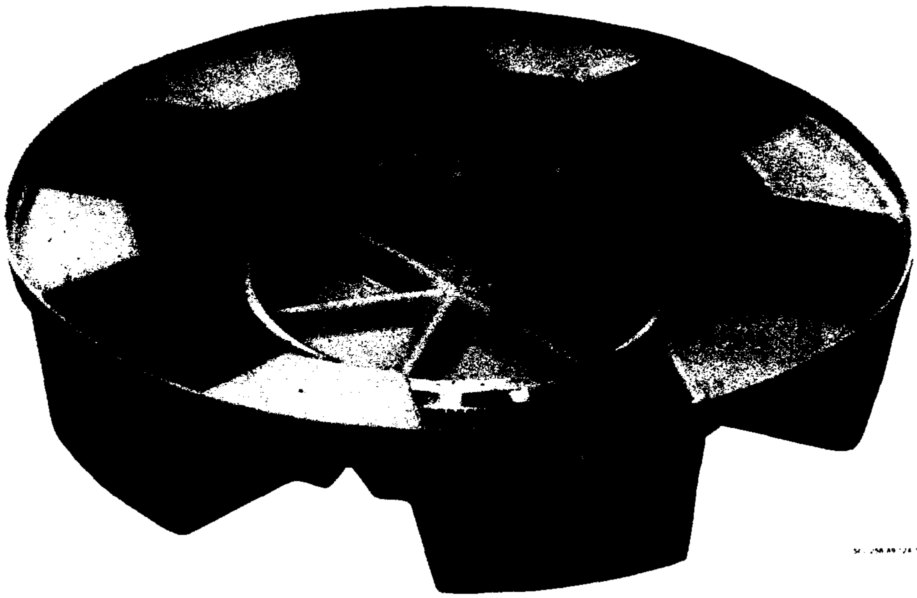
LPT DISC FLANGE RADIUS ROBOT

- Figure 7 -

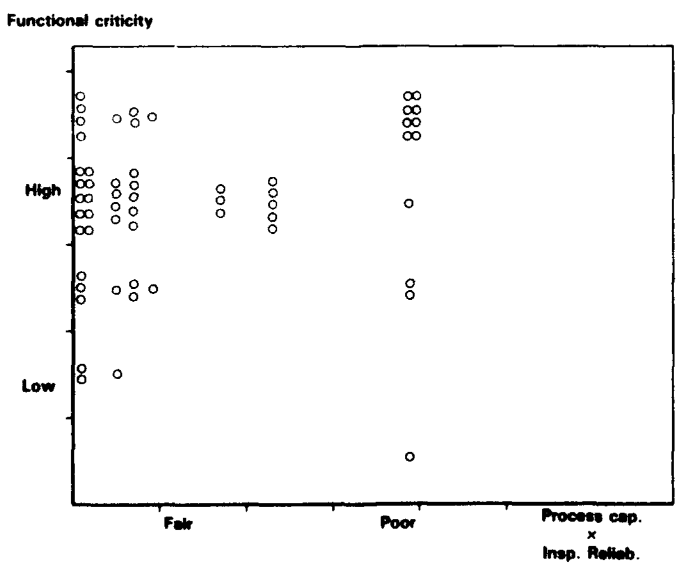


LPT DISC HANDLING

- Figure 8 -



- Figure 9 -



MANUFACTURING PROCESS CONTROL AS A DAMAGE TOLERANCE CONCEPT

by

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The design of a "Damage Tolerant" product consists in assuming that it may contain damages or defects, in determining the characteristics of such damages and defects and in taking appropriate steps so that during the considered service time they can not develop in such a manner that the structural integrity of the product is no longer ensured. Original defects generated by the manufacturing process are undoubtedly part of the damages to be taken into consideration.

Manufacturing process control means a permanent search for the lowest possible variability of the manufactured part characteristics. In fact it tends to a zero "defect" solution, whatever the meaning given to the word "defect", by acting in every field involved (methods, means, workforce, etc.). At first glance, but only at first glance, it might seem contradictory to deal with the role played by process control in Damage Tolerant product design and manufacture : it could be assumed that since defects are tolerable, it should be possible to take advantage of it by reducing the efforts made to eliminate them and, in doing so, to cut manufacturing costs.

Such a strategy is a priori dangerous since the principle which it is based on is scarcely verified in the industrial reality. The increase of the variability of a process rarely reduces the manufacturing costs and it even contains many germs of important additional costs : need for the introduction of additional inspections, increase of investigations to identify non-conformities, increase of reworks and rejections, all these actions leading to a considerable worsening of cycles, inventories and work in process.

In addition such a strategy of "lower process control" would above all be a mistake likely to endanger the very quality of the product designed as "Damage Tolerant product". Process control is as necessary for Damage Tolerance design as for a conventional "safe life" design, or even more, for reasons relating to the engine reliability and operation safety on the one hand and to the life cycle costs on the other hand. We will review these reasons in the first part of this paper.

Furthermore Damage Tolerance contains several concepts which can be used profitably to modify, reorientate and improve the procedures giving access to the required process control. Some of these concepts will be discussed in the second part of this paper.

Necessity of process control :

Reliability and operation safety : punctual defects

Let us first consider metallurgical defects with a punctual or local character, such as grinding, welding or heat treatment cracks, forging folds or tears, microshrinkage or casting blowholes, inclusions or segregations resulting from processing, etc. After a possible "incubation" time which varies considerably and which is imperfectly predictable in view of current modelizations, all these local material discontinuities are likely to develop during use while more or less following the laws governing the rupture mechanics. All things being equal, these laws are such that the residual life of a part is highly dependent on the size of the considered initial crack or near crack. An uncertainty of a few tenths of a millimeter over the initial size can lead to a 50 % to 100 % error in the propagation cycle number before sudden rupture. So the structural integrity of a Damage Tolerant part is derived from the precision and reliability of the determined initial crack or defect characteristics. In general this determination requires non-destructive testing carried out systematically during the manufacturing cycle, then periodically repeated, if required, during part life. The size of the initial defect for which a sub-critical propagation has to be ensured during the considered period then corresponds to the detection probability and confidence levels considered to be necessary and sufficient (for example 99 % - 95 %). The implementation of the methods allowing to obtain these statistical data is heavy and delicate and the results, in terms of minimum detectable defect, sometimes deviate from the designer's wishes. This subject was widely discussed during the first session of the AGARD-SMP working group dedicated to non-destructive testing methods, and it will not be discussed here again. However it must be noted that inspection reliability alone, although essential to Damage Tolerance design, is not always sufficient. Often inspection reliability has to be combined with and sometimes replaced by manufacturing reliability, i.e the risk of a non-detected defect has to be combined with the defect occurrence rate.

Many of the metallurgical defects mentioned above emerge in a context where such a combination is required. In fact in the best case only detection probability levels expressed in terms of master gauges (defect standard flat bottom hole diameter in ultrasonic inspection, machined notch surface in eddy

current inspection, IQI in radiographic inspection, etc.) are accessible and known, whereas a simple or systematic correlation does not always exist between these standard values and the physical characteristics of the metallurgical defect which determine the real residual life of the part.

The case of high pressure compressor and turbine discs processed by powder metallurgy provides a good example of the necessary complementarity between inspection and process control. In fact these parts contain different types of inclusions (ceramics coming from melting furnace, from atomization nozzle, etc.), whose distribution depends on the size of the sieve and the technology of the whole P/M process. For a military engine, the objective of a residual propagation life of some thousands of cycles corresponds to maximum inclusion sizes ranging from 100 to 500 microns approximately, as a function of stress level, temperature, part type and part area, and the inclusion physical characteristics. At the expense of considerable investments and technological developments, not to mention important inspection costs, it is possible, when carrying out ultrasonic (in volume) and eddy current (on surface) inspection, to ensure the detection of "perfect defects" (flat bottom hole, etc.), whose dimensions are consistent with the 100 to 500-micron size searched for.

However, as Fig. 1 shows, the size of the "equivalent perfect defect" (flat bottom hole diameter), as evaluated by ultrasonic testing for instance, is only slightly correlated with the exact dimensions of the correponding inclusion (measured by ultrasonic indication sectioning). Under such circumstances ensuring that residual life (RL) actually corresponds to predicted life is based on a double assertion as follows :

1°) Probability $\geq$ .99 %, confidence $\geq$ 95 % of detecting an initial crack whose propagation life is equal to RL.

2°) Probability $\leq 10^{-4}$ that a part contains an inclusion whose propagation life is equal to RL.

Of course, even when supposing that assertion 1 may be sufficient, a poorly controlled process largely deviating from assertion 2 would have no economic viability and would generate huge rejections during inspections. To control the access to P/M process control there are some indicators for measuring inclusion distribution (or to be more precise a part of it) during the whole process : elutriation and acid dissolution of powders, billet micrography, button electron beam remelting. Fig. 2 shows how intentional actions (changes in equipment, etc.) as well as "external" events (such as production break and resumption) indeed affect such indicators. Fig. 3 confirms the existence of a correlation between these revealing measures upstream of process control and the level of failure during final inspection.

Inclusions inherent to powder metallurgy process should not be considered as an isolated or a very special case. Hard alpha segregations, based on interstitial O, N, C in titanium alloys, complex carbonitride segregations (white spots) in VIM / VAR processed nickel alloys raise similar questions and call for similar solutions. Generally part stress conditions (temperature, stresses) are simply less severe and "tolerable" defects more important. But for all that they are not always easily inspectable and controllable at the required levels.

Reliability and operation safety : non-punctual defects

Although punctual crack-like defects are the first defects to cross the mind when dealing with Damage Tolerance, others also deserve attention. These defects such as dimensional deviations or metallurgical microstructure variations are more general and may ruin the reliability of "Damage Tolerance" design if not taken into account.

Dimensional non-conformities may generate aerodynamic disturbances, modify boundary conditions, natural frequencies and dampings, lessen margins with respect to aeroelastic flutter. This may result in the emergence of a vibration component superimposed on the low cycle stress, the effect of vibration stresses on crack propagation being particularly important. A vibration component reaching only 15 % of the low cycle stress will most of the time have no significant effect on initiation life. However the fact that such a vibration component appears only a few tens of seconds per flight at a frequency of the order of one hundred Hertz is sufficient to divide propagation life expressed in flight numbers or flight hours, by a factor equal to or greater than 5. No factor of safety applied to inspection intervals could cover such a variability ; it is clear that process control has to make sure that, if this type of phenomenon has not been encountered during engine development and certification, it will not be encountered on production engines.

The case of metallurgical microstructure variations is slightly different. Here again strong relations exist between microstructure (grain and hardening phase size and morphology, etc.) and crack growth rates, even if they are often complex and depend e.g on crack size and stress conditions taken into consideration. However an additional difficulty arises : in fact in most cases microstructure variations also considerably affect initiation life, and such an effect is generally of the opposite sign when compared to the effect on propagation life. Microstructure dispersion is then all the more detrimental ; as a matter of fact part operation safety should in no case be detrimental to the economic life of the part. Part operation safety is based on propagation calculations which will be verified if the grain size is important "enough". However an "oversized" grain will impair the economic life. So the introduction of a "Damage Tolerance" concept, in this example, implies an increased need to master grain size variations.
So far we have been dealing with "defects" in the most conventional sense of the word, i.e non-conformity with the specifications defining the product. Moreover it has been clearly evidenced that the structural integrity of parts designed according to a Damage Tolerance concept can not be ensured by the "defect" inspection only. In this respect process control is certainly an essential tool to add to inspections and the only way to make sure that a part will actually have no "non-tolerable defect". However process control is not restricted to guarantee the part capability to meet specifications ; it also aims at reducing product variability within the tolerance range and is very useful for Damage Tolerant parts for reasons which in a way generalize the case of microstructures dealt with above.

Life cycle costs control

Dispersion of part characteristics (either metallurgical or dimensional or surface characteristics, etc.) is, along with the variety of engine operating conditions, at the very origin of the dispersion of initiation and propagation life which could be noted if engines were operated in an "utmost" manner. In a conventional "safe life" concept, many critical rotating parts (discs, shafts) have a limited life obtained by applying a safety factor to the predicted life (based on calculations and tests) of the minimum characteristics part. So relations between Process Control and Life Cycle Costs do exist but partially and sometimes thoroughly in so far as it is difficult during a program life to express a reduction of generated characteristics variability in terms of an increase in predicted life or a reduction of the safety factor. Inversely an insufficiently controlled part whose real life would be inferior to the predicted life may not be problematic as long as the safety factor makes up for insufficient control, and lead to a disastrous situation if limited life itself is no longer ensured.

In the Damage Tolerance approach, relations between Process Control and Life Cycle Costs become more direct and more continuous as well. When exploited in its integrality (Retirement for Cause), this concept may be extended to the point that operation without any other limit than the real life (at maximum tolerable damage detection) is allowed. In such a situation, any characteristics dispersion will directly affect the actual operation time of the parts ; excessive dispersions leading to an unexpected high number of "unscheduled" removals would bring about extremely serious consequences in the logistics field.

Either the risk of operation unavailability should be accepted or considerable spares floats should have to be constituted as a coverage : the profit expected from the Damage Tolerance / Retirement for Cause concept would be cancelled, or even would turn into increased life cycle costs.

Therefore Damage Tolerance design requires, from an exclusively economic viewpoint, to tend to reduce as much as possible (initially tolerable) "small defects likely to turn into big ones". As a result since inherent non-propagation thresholds are rather low, scratches and handling damages, blending radius profile deviations, peening rims, etc., are continuously tracked down. Examples of fatigue cracks initiated on such "defects" during rig tests are represented at Fig. 4 and 5. It is certainly difficult to remove them completely but significant progress can be made provided the need for it has been recognized. Fig. 6 shows how it is possible to progress in blending radius profile control applied to LP turbine disc slots and scallops. A first important improvement has been achieved in setting up integrated inspection enabling the performer himself to inspect the quality of rounded edges and therefore to react almost in real time. A second step of improvement seems to take shape with the automation of radiusing operations which provides better repeatability potentialities (Fig. 7). Another example in Fig. 8 shows that new packaging designs adapted to turbine discs have led to a noticeable improvement of surface condition, thus significantly reducing the number of necessary reworks following impacts and handling damages.

Damage Tolerance contribution to Process Control

As already seen, Process Control is highly necessary to a Damage Tolerance approach. Naturally conventional tools to access to this type of control apply perfectly :

- statistical follow-up of products, processes and resources
- preventive maintenance, resource reliability analysis
- quality action groups
- process modelization
- etc.

However the Damage Tolerance concept certainly makes it possible to tackle the conventional issue of a "compromise" between design requirements (specifications) and process capabilities from a new point of view.

As an example let us trace back the procedure followed for a single-crystal (AM1 alloy) HP turbine blade characterized by very thin walls, a sophisticated inner cooling and a high operating temperature (1850 K TET). Once the first twenty blade sets have been manufactured and the first hundred hours of development tests logged, a multi-function working group (Design Office - Process Engineering and Manufacturing Workshop - Quality) carried out a kind of "product review" according to the following methodology :

. 49 specifications (analyzed, of any kind : metallurgical, etc.)
. 3 criteria : - Operating criticality
  - Manufacturing process capability
  - Manufacturing inspection reliability
. 4 or 5 rating levels :

- For operating criticality :

  5 - Effect on airworthiness
  4 - Effect on life cycle costs and performance
  3 - Other effects
  2 - Margin ≥ 50 %
  1 - Margin ≥ 100 %

- For manufacturing process capability and inspection reliability :

  5 - Non-capable process, non-reliable inspection ; need for innovations.
  4 - Capability margins, detection probability to be improved
  3 - Variability to be improved for cost effectiveness
  1 - Process under control

Such ratings were performed e.g from records of the statistical process follow-up : rejection rates, reworks, histograms and flow charts, etc.

As a first step each of the 49 specifications was transferred to a Process Capability / Inspection Reliability diagram which makes it possible to identify the points for which an immediate action has to be taken. The 49 characteristics were then placed on a Functional Criticality / Process Capability X (*) Inspection Reliability diagram (Fig. 9). On completion of this analysis, the working group made 55 proposals split up as follows :

- 13 specification reviews
- 26 modifications of manufacturing and inspection methods, (7 of which were major ones i.e inducing investments)
- 16 programs of rig or engine tests intended to verify, if required, the "tolerable" aspect of certain variations.

Such an approach indeed consists in ensuring Defect Tolerance and through its comprehensive character it brings together and corroborates everyone's effort, with the customer's satisfaction as the common ultimate target. Of course such an approach can also be very profitable when applied at the very beginning of design (initial drawings), even if it has to be reajusted during development, as the experience acquired from production and tests delivers precisions on the defects specific to the part and on their particular behavior on the engine considered.

From a similar viewpoint Damage Tolerance concepts can also provide new opportunities to widely propagate within the company links between the quality of everyone's work and the product behavior in operation. As an example we set up a training course on "fatigue and rupture mechanics" meant for the largest possible audience of engineers and technicians coming from activity sectors as various as possible : project or program department teams, laboratories, process engineering, workshop supervising personnel, product support technical departments, etc.

The 4-day training includes an extremely rudimental theoretical course on stresses in turbine engines, fatigue and rupture mechanics laws as well as a statistical overview of structural failure sources for engines in operation. Above all it includes several "case studies", drawn from real investigations performed after ruptures during operation. Of course such studies have been simplified or complemented for the purpose. In analyzing the cases the participants who work in groups are led to :

* identify and understand the initial reasons for the structural failure

* verify the influence of defects on initiation and propagation life by means of very rudimental calculations

* compare such calculations with data resulting from fracture tests (striations, rest lines, etc.).

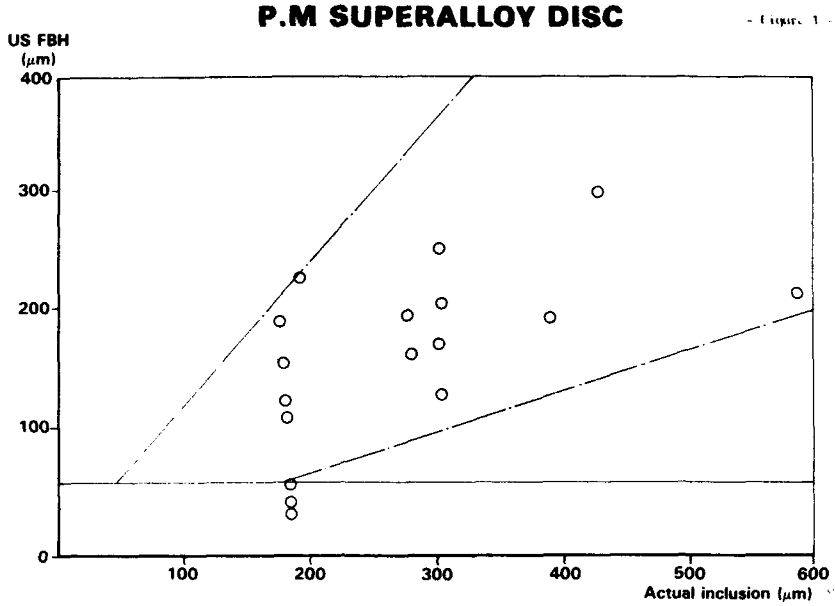
* propose on a Damage Tolerance basis procedures to maintain in service materials featuring the same potential failure causes : selection of inspection techniques and inspection periodicity, etc.

* evaluate the logistic consequences of such procedures at the customer.

Even though the participants do not become experts in Damage Tolerance, they acquire a far better insight into this aspect of phenomena and mechanisms occurring upstream, downstream and in their everyday work. So they have a clearer and closer understanding of the effect of these components on the end customer's satisfaction. Since it is more motivated, the trained personnel has the possibility to be deeper and more consistently involved in the entire industrial process of design, production and operation.

Finally Damage Tolerance applied to aircraft engines appears both as a further "urging necessity" to progress in process control and as the opportunity to open up new ways to achieve such a control.

(*) Other combinations of these two criteria are possible.



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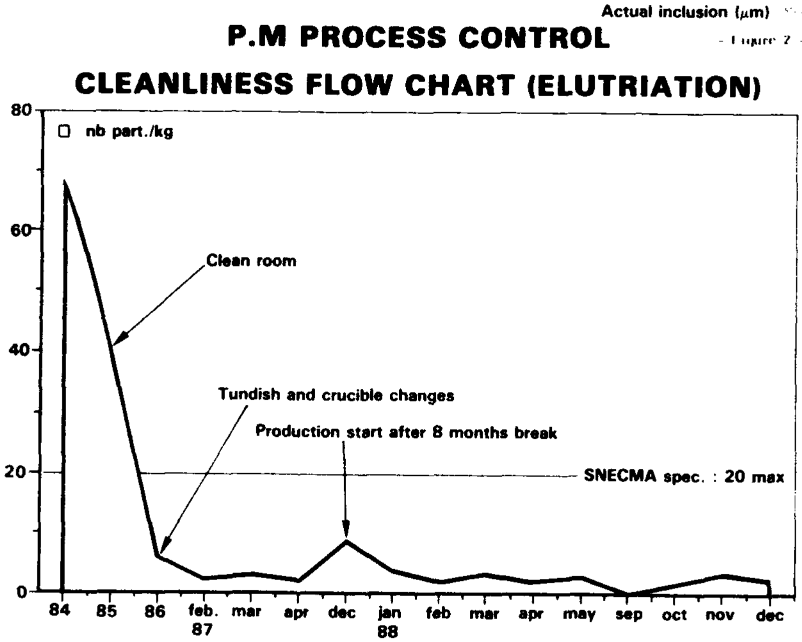

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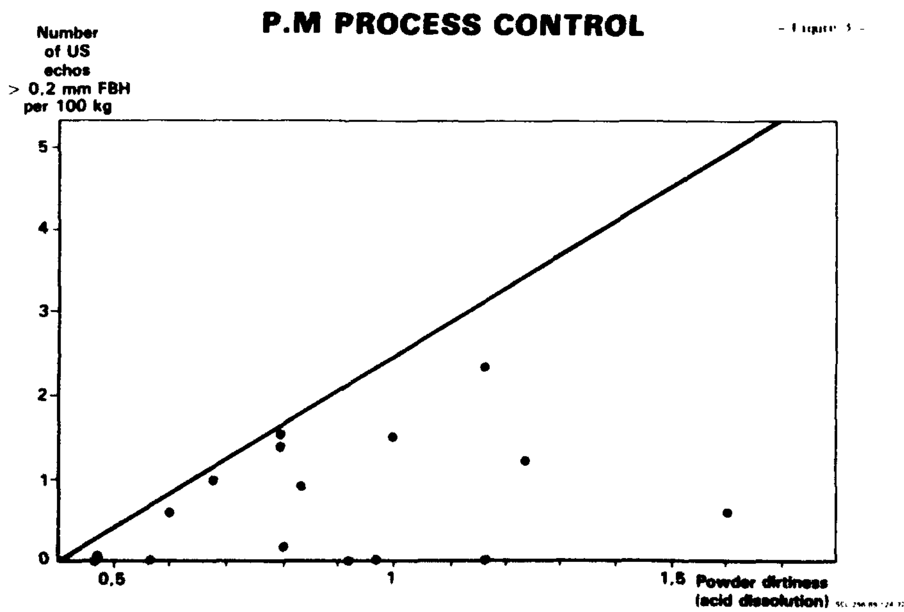
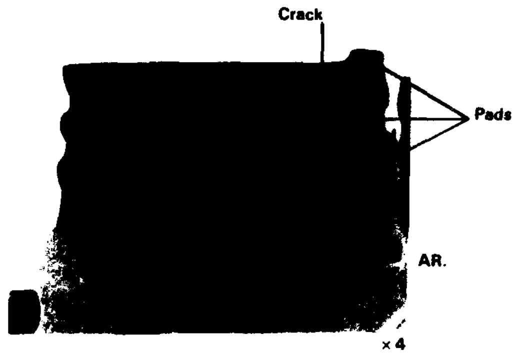


- Figure 3 -

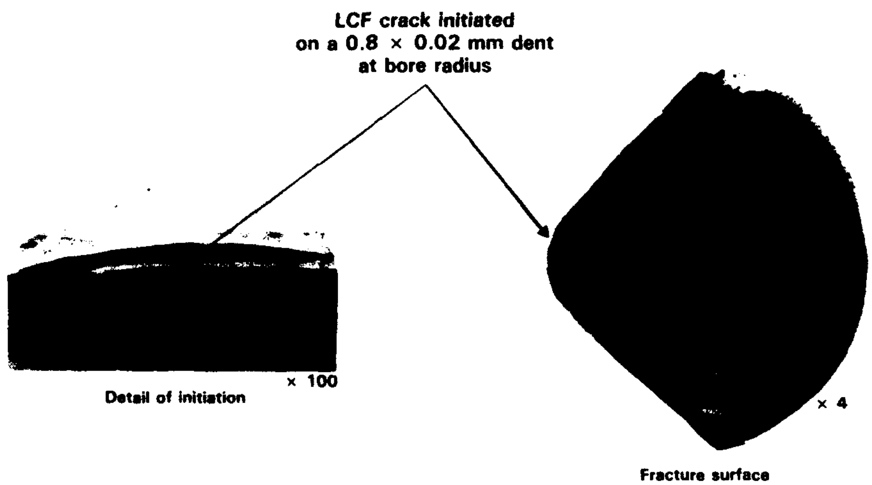
HPT DISC : LCF DOVETAIL CRACK INITIATION ON SHOT-PEENING PADS

- Figure 4 -



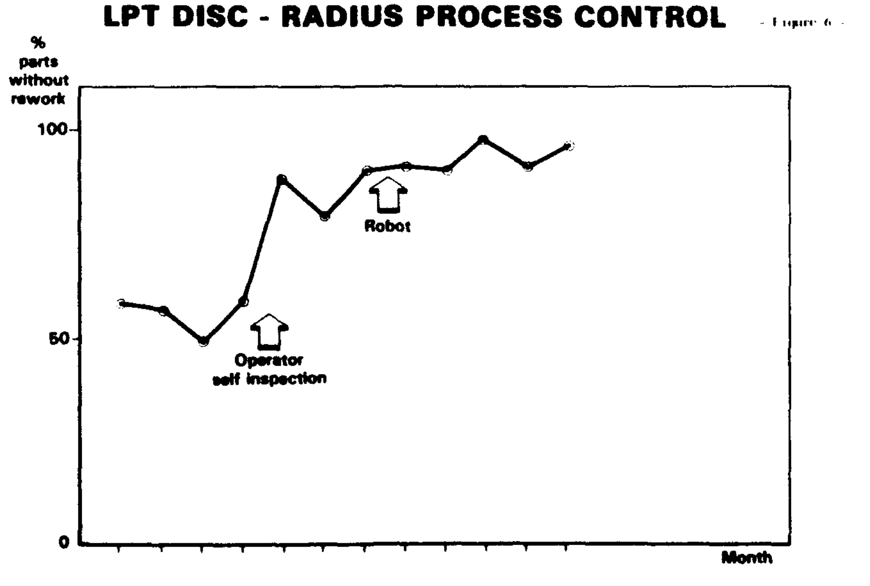
P.M HPT DISC

- Figure 5 -



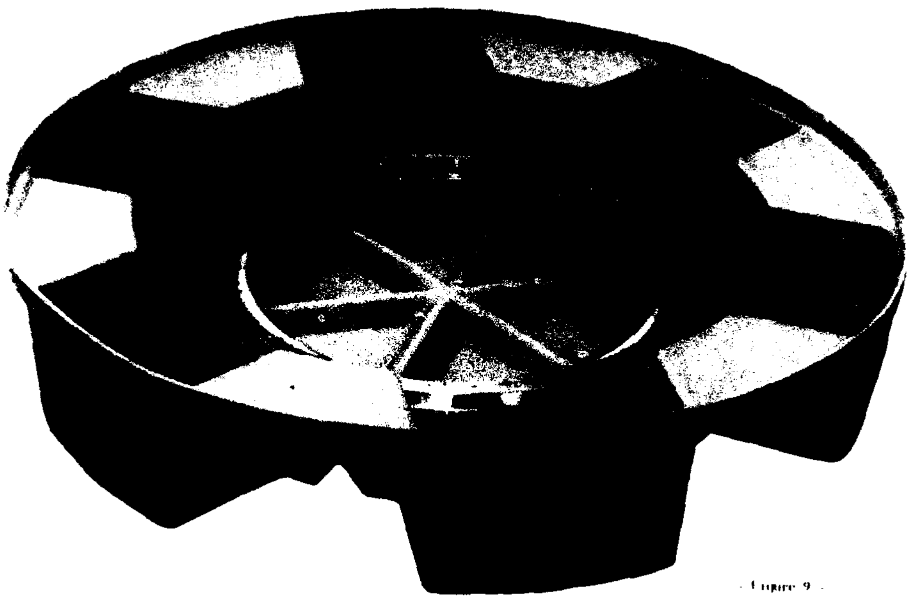
LPT DISC - RADIUS PROCESS CONTROL

- Figure 6 -

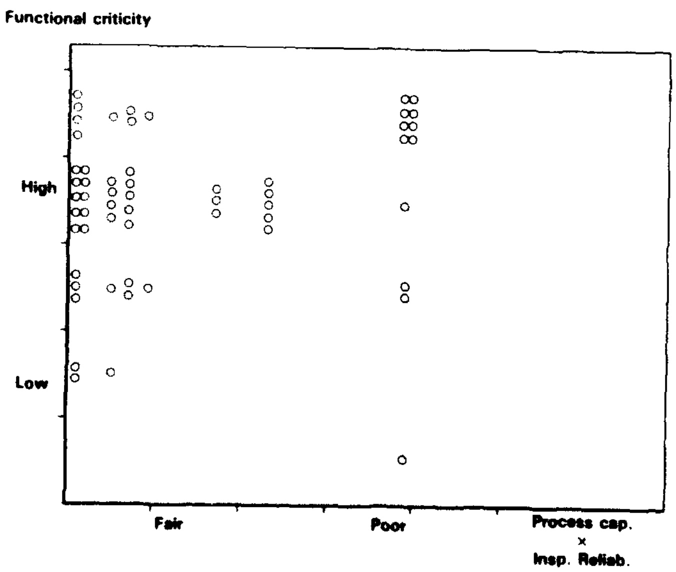


LPT DISC FLANGE RADIUS ROBOT - Figure 7 -

LPT DISC HANDLING - Figure 8 -



- Figure 9 -



QUALITY ASSURANCE AND DESIGN SYSTEMS

by

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SUMMARY

Inside the company quality system as outlined by NATO AQAP-1, a major role is given to engineering quality. This is the branch which is responsible to give assurance that a design and development program is set, codes of design practice are established and maintained, drawings and specifications include all practical experience gained by the company.

The Engineering Quality Manual and the Design Manual are the reference for such activities. The Engineering Quality Manual in fact sets the methodology to be used in the project development. The Design Manual, on the other hand documents the technical data and information to support material choice, structural analysis, life prediction.

An example is given to show the type of content of the Design Manual within the subject of damage tolerance criteria of rotating critical parts.

1. COMPANY PROFILE

FiatAvio carries out aero-engine business with a tradition dating back to 1908 and since continued without interruptions.

The Company headquarters and main manufacturing plant are located in Torino; other plants are in Brindisi (southern Italy) and in Torino vicinity.

FiatAvio has full capability in design, development testing, manufacturing and product support relative to major sections of military and commercial aero-engines.
Full responsibility is held by Fiat also for complete auxiliary power unit and for space applications such as the APU for the AMX aircraft and the oxygen turbopump of main engine of Ariane 5.
Specific involvement in design and manufacturing is also that of the helicopter main power transmission field.
Finally great importance is given to the production under design responsibility held outside FiatAvio such as those for major sections of commercial engines, for complete military engines, for overhaul of Italian Air Force engines and last but not least for industrial gas turbines.

2. DESIGN MANUAL CONCEPT IN FIAT AVIO

The summary presented hereabove shows how FiatAvio, like most free-world aerospace companies, is significantly involved in design engineering; this has become more and more due to the need of maintaining products in line with a fast and demanding progress.

As a consequence of this evolution, also in our company the basic quality concepts and techniques find new and complex applications.
A special application of these is to design engineering activity.
FiatAvio has recently implemented an interesting program to this effect.

Subject of this paper is a summary of the concepts developed by FiatAvio to control quality in engineering activities, and the description of a specific application of this concept in the field of DAMAGE TOLERANCE criteria for rotating fracture critical parts lifing.

The strategic decision to address our activities to products designed by FiatAvio has had a heavy impact in the company.

For license production FiatAvio to implements the quality concept mainly as conformance to a design with known characteristics and performance. This is assured by proper actions both at prevention level in all technical departments and at verification levels through the necessary inspections.

On the other hand where we hold full design responsibility same concepts have to be applied. In fact we cannot afford to simply check the final product for conformance to the applicable requirements. The long time span and the very high costs necessary for the development of new products from preliminary design through qualification requires to keep under proper control the whole company's technical process.

Within this evolution, Design Engineering is the hinge of the company's approach. This is the function through which the product is conceived and therefore it has to be open to all new technical acquisition and to be capable of capitalizing the company's experience on established know-how.
Design Engineering should therefore blend more and more with the other company functions through a mutual exchange of experience and methods.

The basic principle of the Engineering Quality program is that the output of this function can be compared to that of a complex system. This is confirmed by the fact that its quality level cannot be assessed by a simple analysis of the final output.
Such assessment can in fact only be performed through a system capable to ensure all activities upstream of the final product (i.e. drawing, specification, test, etc.) are under complete control.

Rather than performing verifications on the final outputs, it is necessary to emphasize an engineering sensitivity to quality; such sensitivity should become a basic element of this activity.
Consolidating this sensitivity is the main objective of the program and includes all Design Engineering activities through the definition of accepted methods.

It starts from preliminary design with the objective to define methods and procedures to ensure the general airworthiness and contract requirements are identified, critically examined and explicitly assumed from the initial design phase.

Moving to the subsequent step of finalized design, procedures and hence organization channels must be identified to ensure a continuous comparison of the developed product to the initial design concept: this guarantees that the necessary changes introduced during the development phase are in line with the initial definition, i.e. with the reference specification.
Final design is in itself a complex process and should use precise methods.

The design engineer should in fact have consolidated design criteria as guidelines and use only qualified theoretical analysis and design methods.
This in fact ensures that, without limiting individual creativity, the methods used have been checked and approved for effectiveness, accuracy and cost. Theoretical analysis methods, for instance, should be considered special processes which must be qualified, i.e. their boundary conditions, operation, accuracy and output must be assessed and found acceptable.

Also experimental work has to be controlled through applicable specifictions, activity flow path and performance of test work.

This means that the complex design engineering activity has specific guidelines and instruments, the performance of which is the responsibility of the function itself, and a development activity flow-path rationally consolidated.

This allows to plan suitable verification steps with specific acceptance criteria and to schedule and control, even time-wise, interlocked and highly complex activities.

In such a scenario, Quality cooperates very strictly with Design Engineering, and maintains full responsibility for quality also in this area. This is achieved through the Engineering Quality function which is part of Engineering with a functional reporting line to Quality.

In this area two basic instruments have been identified:

- the Engineering Quality Manual
- the Design Manual

The Engineering Quality Manual is devoted to the definition of the procedural aspect of engineering operation. Therefore it contains the description of the activities with their relevant flow diagrams, the definition of interfaces, the detail responsibilities, the engineering quality control features and responsibilities.

The Design Manual on the other hand is concentrated on the content of design. It has the aim of consolidating and updating the scientific and technical knowledge with special regard to lessons learned from experience.
It is a major tool to support technical decisions and their proper delegation. But it has also a specific objective of helping training of engineering personnel. Finally through the dedicated check-lists it is a mean of engineering quality control and a directive for design reviews.

The Design Manual is structured by individual monographies covering separately homogeneous subjects.

As an example, we have summarized the content of chapter "Lifing-Damage Tolerance" included in the Turbine Disks monography which is being prepared by Engineering Department.
The content is by nature dynamic and is continuously improved and evolved. The example is however representative of the type of content our design manual is based on.

3. EXAMPLE OF IMPLEMENTATION

3.1 TURBINE DISKS FAILURE MODES

Turbine disks of advanced turbojet and turbofan engines are high speed rotating components whose failure would yield high energy fragments, likely uncontained by and inside the engine turbine casing(s).
Since such a failure would constitute a hazard to the aircraft safety, turbine disks are classified as fracture critical parts; their structural integrity must be guaranteed with a high global safety level against all the possible failure modes.

In the design phase the following failure modes are considered:

Permanent set
Bursting
High Cycle fatigue
Low Cycle Fatigue

While for the first three modes design criteria are well assessed and basically common to all aeroengine manifactures, lifing criteria related to low cycle fatigue have evolved from the conventional safe life approach after the introduction of high strength alloys like those based on powder metallurgy.

Life prediction reliability depends on the procedure itself as well as on the confidence of the engine operating conditions definition, the methods of stress and temperature analysis, the material design data.

In the following paragraphs the lifing methodology adopted by FiatAvio will be treated, as well as some results of the planned activities to verify the criteria.
This methodology is considered as the basis; if necessary it will be modified to meet the requirements of specific projects. Emphasis will be given only to those features which make advanced materials lifing different from the traditional ones.

3.2 LIFING CONCEPTS AND PROCEDURES

The most general fatigue lifing approach is based on the total life concept.
With reference to a component critical area, the useful cyclic life (N_t) is given by the two terms corresponding to crack initiation and to crack propagation (N_p):

$$N_t = N_i + N_p$$

The reliable service life (S) can be established by spinning tests (using a reference stress cycle) to determine the experimental cyclic life (N), taking into account the fatigue life scatter factor (y) and the mission exchange rate (ß):

$$S = N/_{y.\beta}$$

where S is in operating engine hours.

The two values y and ß are not rig test results, but they are previously assessed on the basis of material data and design missions.
The theoretical treatment of the fatigue phenomenon as well as the experimental findings suggest to refer y and ß to the fatigue life stages (initiation and propagation):

$$S_t = N_i/_{y_i.\beta_i} + N_p/_{y_p.\beta_p}$$

When only the first term is considered, the approach is "SAFE LIFE" type, whereas by considering the second term only, the lifing method is "DAMAGE TOLERANCE".

According to the remote probability level required for turbine disks fracture, yi value is about 10 for conventional nickel alloys, about 100 for powder metallurgy alloys.
The very large scatter factor of PM alloys is shown in fig.1 with reference to the Astroloy LC PM alloy.
It is evident how for advanced high strength alloys, the crack initiation life demonstration is not an efficient way to assess the component life.
FiatAvio has adopted the method to demonstrate turbine disk life on the basis of crack propagation only; in line with this, preflawed disks are spun up to the critical crack size in order to demonstrate the propagation cyclic life.

The flaws have to be obtained by appropriate methods and the induced crack sizes must be of the order of the remote probability defect size assessed for the specific component or material.
In accordance with the major european aeroengine companies approach, the initial defect size assumption is based on the intrinsic material defect distribution, related to characteristic features of the material process and its control.

The test method mentioned above is applicable only to surface critical areas; if internal areas are the most critical, the test results obtained on surface preflawed disks should be properly factored.

Corrective factors are also to be applied to take into account any difference between the artificial crack size and the size of the most severe intrinsic one.

In conclusion, cyclic growth life Np has to be determined by preflawed disks spinning; the corresponding safe cyclic growth life is obtained dividing by the scatter factor yp.
For all the materials of interest, the crack propagation scatter factor is yp = 2. It could be omitted in the case it can be justified by the initiation life analysis, based on S vs. N fatigue curves obtained using specimens, when Si ≥ Sp.
The above indicated allowance about yp is the first step towards the total life approach which has to be used only when sufficient experience has been accumulated and test data both on specimens and disks are available.

The exchange rate evaluation (ßp) has to be done on the basis of engine missions, using an ad-hoc computer code developed on the basis of fracture mechanics concepts and experimentally verified.

3.3 MATERIAL DESIGN DATA

Material structural properties are established by test on specimens from "as produced" parts.
Additional data required by the damage tolerant approach are the cyclic crack growth data (da/dN vs K curves), fracture toughness (Kc) and the defect size distribution.
Fracture mechanics data are typical (average) values since in the damage tolerant approach the required high safety level is achieved mainly through the assumption about the most severe initial flaw size.

The defect size distribution is derived by the scanning electron microscope fractography on low cycle fatigue test specimens (an example is shown in fig.2).
By focusing on the crack initiation site, if crack nucleation is caused by embedded inclusions, the size will be determined relative to the axes of the ellipse which circumscribes the actual flaw within the stress plane. Then "penny shaped" crack size (radius) is established, equivalent to the elliptical one in terms of area: their equivalence in terms of fracture mechanics is demonstrated.
For surface inclusions and corner inclusions, the shapes to be used are the semi-ellipse and the quarter-ellipse, with the equivalent radius of the semi and quarter-circle respectively (see fig.3).

All equivalent defect sizes constitute a set, by ranking the values it is possible to associate to each set element a cumulative occurrence probability and then by using a proper statistical distribution it is possible to extrapolate from the esperimental defect size the design size with the required remote probability of occurrence.
Fig.4 gives an example of the defect size distribution obtained using the method here illustrated; the same approach can be adopted for other defects (pores, ppb's, inclusions clusters, etc.) if their severity is such as to generate fatigue crack initiation.

3.4 PROCEDURE TEST

The lifing procedure summarized in paragraph 3.2 has to be tested in its relevant assuptions and codes before it can be used for production engines.

Three elements are important:

- short crack behaviour
- stress intensity factor evaluation
- exchange rate

It is well known that fatigue crack propagation data obtained by conventional ASTM specimens are not applicable for short crack behaviour.
In order to avoid possible limits in the crack growth data application it has been decided to characterize the material by testing specimens with crack size similar to the most severe intrinsic defects.

The specimen adopted is the corner crack one, calibrated in the TX114 programme, which allows crack size less than 100 micron and which guarantees the full validity of the crack growth data obtained.

If the evolution of powder metallurgy alloys will allow to obtain cleaner materials with smaller defect size than the present ones, the calibration of the corner crack specimen would have to be extended down to the new defect size level.

The stress intensity factor evaluation is presently based on nominal stress distribution obtained by MSC/NASTRAN Finite Element code and on the parametric shape

factor formula derived by technical literature.
Even if F.E. analysis were used directly to derive the stress intensity factors, for instance by the special elements provided by advanced F.E. codes, it is fundamental to experimentally verify the stress intensity factor.
This will be done by comparing the crack growth curves obtained respectively for a well characterized specimen and for a preflawed disk, when both are fatigue cycled within the same stress range, provided they are of the same material and the disk surface conditions do not significantly affect crack growth.
Last but not least, the exchange rate evaluation is to be considered.
The damage tolerance approach introduces a certain number of aspects which should be taken into account in order to analyze complex stress spectra.
Such aspects are mainly related to sequence effects, retardation, crack closure.
Also the general validity of the related algorithms must be tested because of the difference between βi and βp for the same stress spectrum.
Fig.5 shows the experimental results obtained by FiatAvio in a specific testing program designed to validate the βp evaluation code.
Crack growth rates were measured on corner crack specimens using a constant amplitude load and a complex spectrum related to an actual engine usage.
The comparison between the crack growth per mission and the crack growth per reference cycle is very much in line with the previous exchange rate evaluation obtained by the FiatAvio code.

4. CONCLUSION

This presentation was aimed at indicating the basic concepts of FiatAvio system to control design engineering activity.
The system is based on the preparation and on the use of a technical instrument, the Design Manual, and on an organization instrument, the Engineering Quality Manual.
The final certification should confirm that the design has been performed in line with both Manuals guidelines.
Both of them are the tools to control step by step the complex process of design within the development plane.
Final assessment of the design is therefore reached through the progressive accomplishment of controlled steps, thus minimizing the technical risks concerned with the development plane.

Therefore this Design System contributes to Quality concept implementation for the benefit of both the Customer and the Company itself.

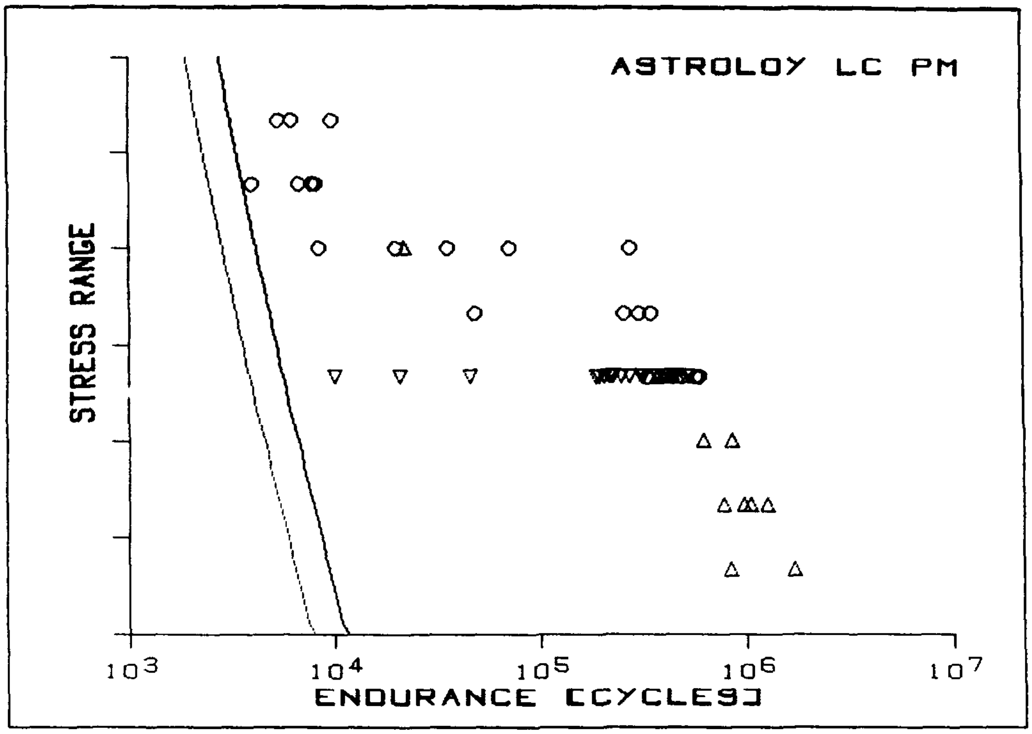

Fig. 1 LCF results at 500°C on powder Astroloy LC (line represent fatigue crack growth prediction)

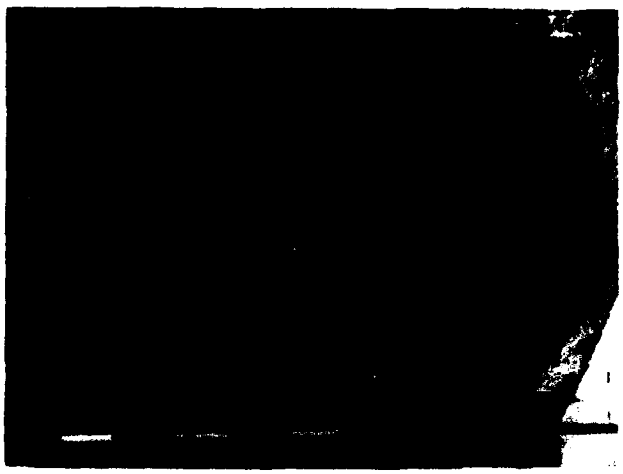

Fig. 2-a Fatigue crack initiation site obtained by SEM on LCF specimen

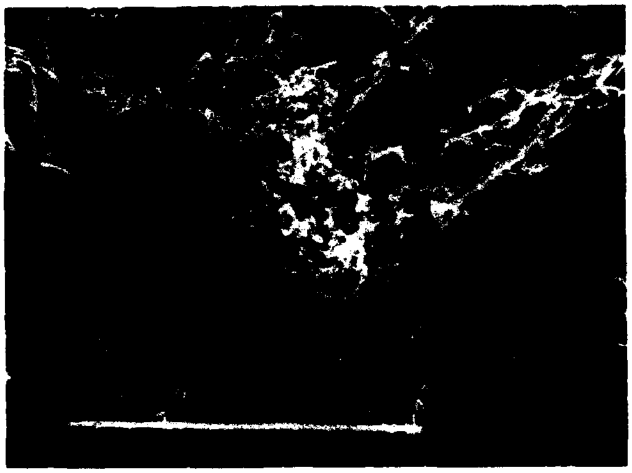

Fig. 2-b Analysis of the crack initiation defect

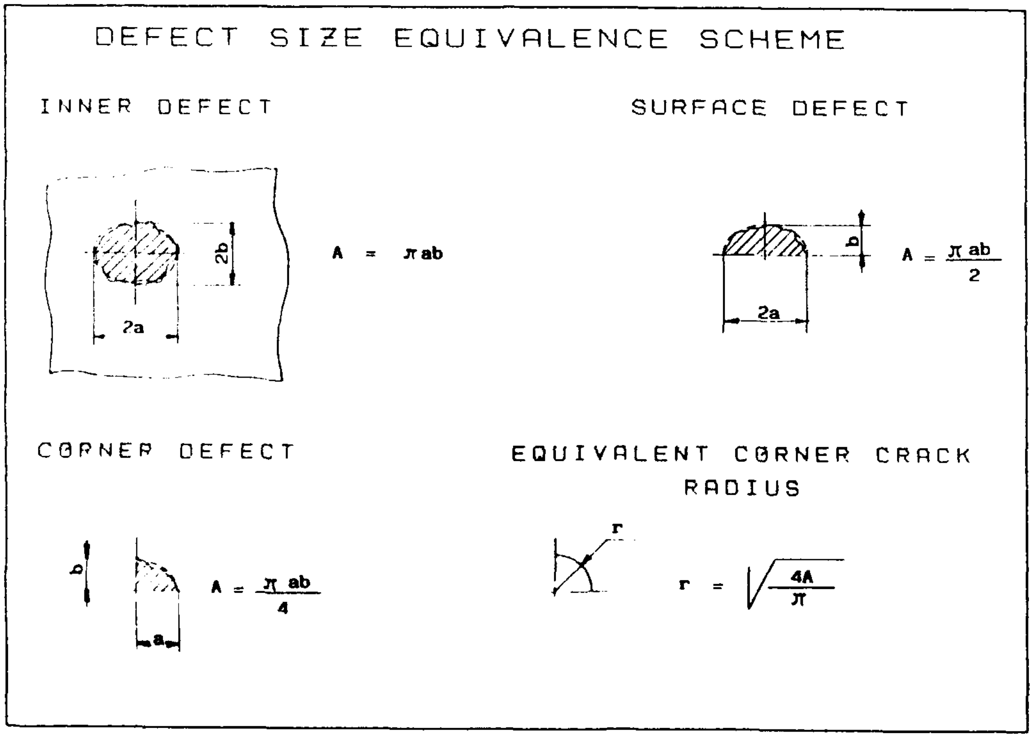

Fig. 3 Equivalence scheme for defects with different location

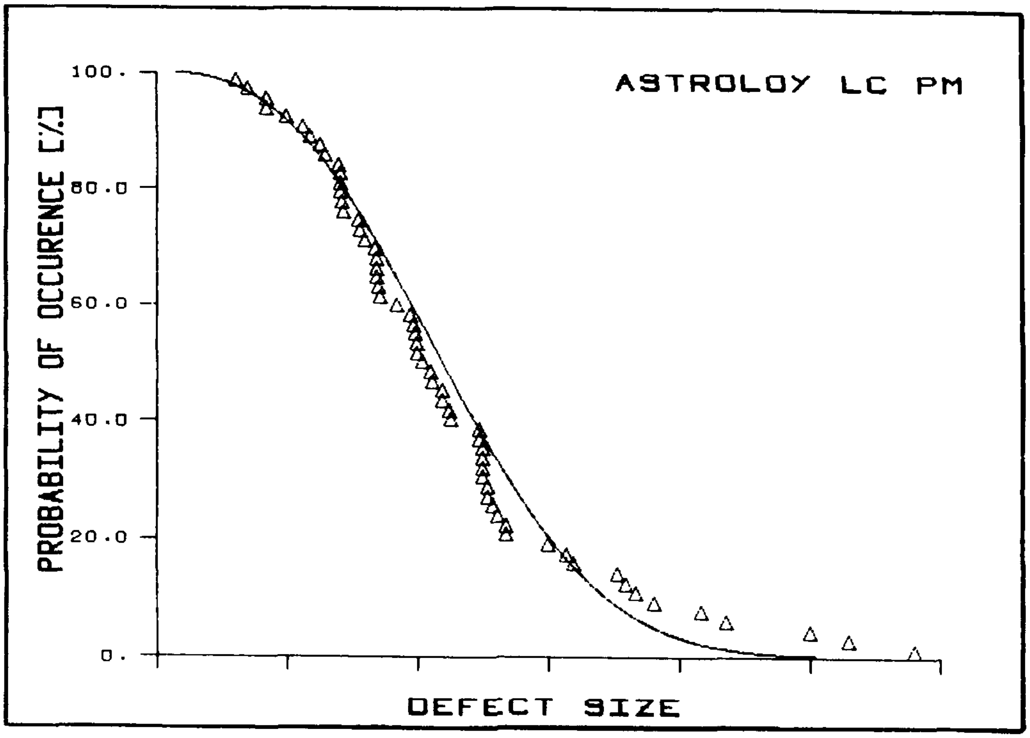

Fig. 4 Statistical distribution of the most severe defects size obtained on powder Astroloy

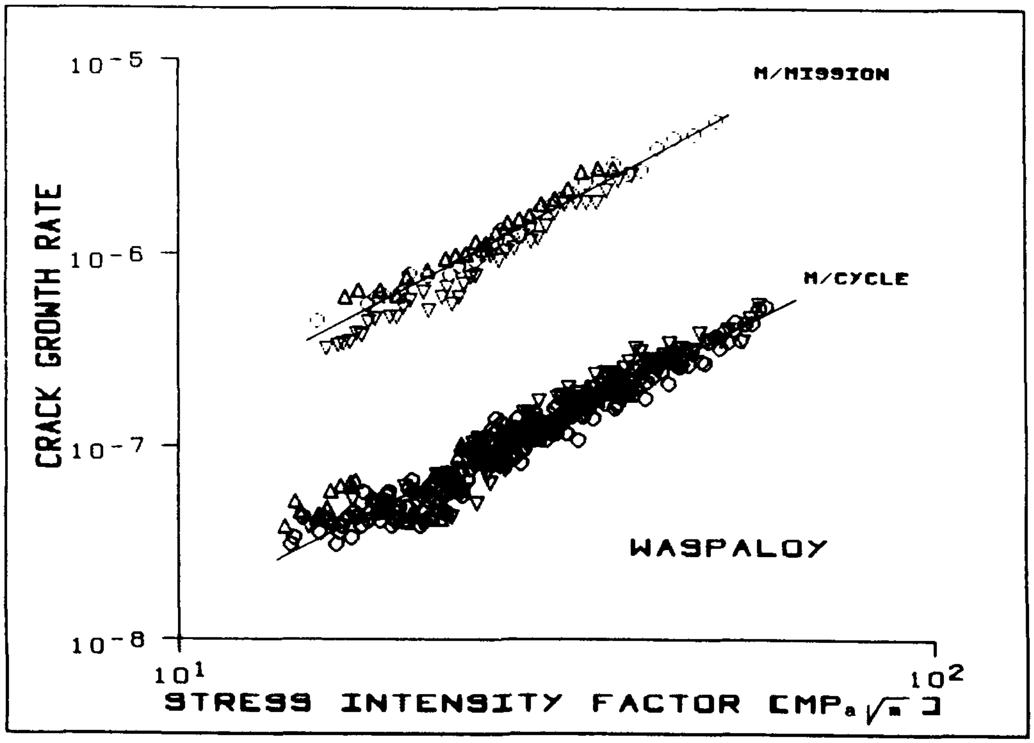

Fig. 5 Experimental growth rates obtained by cycling with a constant load range and a complex spectrum vs max stress intensity factor at 450°C (data obtained by Pisa University on behalf FiatAvio)

Summary of the discussion (last session of Workshop IV on Damage Tolerance for Engine Constituents).

The Workshop addressed five topics :

- Introduction - Needs and Approaches to Reliability and Quality Assurance
- Component/Materials Specifications and Standards
- Control of Manufacturing Processes and Procedures
- Quality Assurance and Design Systems
- Common AGARD Approaches and Actions.

A general discussion (reviewing the conclusions and points made during the previous Workshops) helped in identifying subjects for future AGARD cooperation, namely :

- Establishment of a database on Defect Distributions (including handling damage).
- Assessment of the Effects of Defects, taking into account environmental conditions and short crack behaviour.
- Review of statistical methods used in NDE.
- Action trying to answer the question : are NDE techniques quantitative rather than qualitative,
- Investigation of models describing the basic behaviour of materials.
- Customer's point of view on Retirement-for-Cause acceptance.
- Development of New Materials and Procedures - consequences on damage tolerance approaches.
- Tentative review of a closer insight of Damage Tolerance Basics.

Recorders' Report

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1. General

This fourth and last workshop of the Series again showed that the USAF-ENSIP-Damage Tolerance Approach is viewed with somewhat less enthusiasm by European gasturbine manufacturers than by the USAF and US manufacturers: While both sides stress that the effect of defects on durability of engine components is extremely important, the ways of dealing with defects are different:

- The USAF and its suppliers in the Engine Structural Integrity Program assume cracklike defects to be present from manufacture onwards. NDI must detect the size of defects with an agreed degree of confidence. This approach is now mandatory for future USAF gas turbines.

  However, NDI is additionally used for process control, and in certain engines, for RFC (Retirement For Cause).

- The European manufacturers in the first place try to avoid such defects by manufacturing process control. In the U.K., for example, NDI is used in a process monitoring role to prove during development that the manufacturing process is viable, and, during production, to monitor that it stays within acceptable limits.

The USAF contribution (Cowie, see below) impressed the recorder - like many previous USAF papers on ASIP or ENSIP -

- by the huge amount of data available on every important parameter, like NDI - capabilities, crack propagation properties of relevant materials, etc.,

- by the continual improvement of NDI-capabilities and material properties over the last 10 years and

- by the logical and consistent way of identifying, attacking and solving the many problems inherent in this approach.

One reason for the (in the recorders' opinion) superiority of the USAF approach probably is the much stronger position of the USAF as a buyer in a huge market, because of the larger number of aircraft (and engines) of one type. The high additional first cost of proving the viability of ENSIP is thus justified by the much smaller life cycle costs of the many engines involved.

In contrast, the European Airforces buy smaller numbers of aircraft of one type, have a weaker position versus their manufacturers and cannot spend so much money on a (to them) new method of ensuring structural integrity of engines.

2. The papers

2.1 Introduction - Needs and Approaches to Reliability and Quality Assurance in Design and Manufacture - Pickard, Rolls Royce, U.K.

Pickard gave an overview over the previous three workshops and again stressed the need for common Agard Approaches and Actions, for example:

- the establishment of a database on defect distributions (including handling damage),
- the assessment of the effect of defects, accounting for environmental conditions and short crack behaviour.
- a review of statistical methods employed in NDI etc.

Although no firm decisions were taken at the Workshop itself, in the meantime several Agard SMP activities in the above fields were discussed or are at the starting point.

In the discussion period of this paper, the imperative need to agree on design spectra was stressed. Without correct design sprectra, no approach will work, as shown by the severe structural problems of several modern tactical aircraft, where the design spectrum was not as severe as actual usage.

2.2 USAF Engine Structural Integrity Program (ENSIP) Status - Cowie, USAF

Cowie first reported on the evolution of ENSIP and about some lessons learned, among them again the importance of correct spectra for design, component tests and full scale engine tests.

The quoted weight increase of 20 lbs for all rotating parts of an engine due to the DT requirements was questioned in the discussion period. The answer was that this was an actual weight increase, although the DT requirements would size the part, not the LCF (durability) requirements.

The continual development of NDI capabilities mentioned above was shown in a few examples: For six different materials the

detectable flaw size (with the usual 90/95 requirement) decreased from about 1 mm to 0,25 mm from 1985 to 1990.

In the materials field, the trend of using materials with higher yield strengths and consequently worse crack propagation properties was reversed (at least in one case): A five percent lower yield strength was allowed and the burst speed requirement of 120 % was relaxed to 117 % to obtain better crack propagation lives, namely from 4000 to nearly 10000 cycles. In this case of the F-100 engine, for a 1 % weight increase, savings of more than $ 300000 per engine due to reduced maintenance, increased parts life etc. were realized.

Accelerated mission testing and how to accelerate it compared to service without overloading the component was mentioned in the discussion period. The answer was "by omission of nondamaging events".

2.3 Manufacturing Process Control as a Damage Tolerance Concept - Herteman, SNECMA, France

Herteman distinguished between flaws during manufacture, which MPC can exclude and cracklike flaws, which develop during service.

The difficulty of not only detecting a flaw but also determining its actual size was shown, where in the worst case the actual flaw sizes were three times larger than the indicated ones.

"*Dimensional nonconformities*" *also can* be avoided by MPC. If they occur, they may cause additional low vibrational stresses of a high frequency, which may result in a reduction of the crack propagation life by a factor of up to five.

All this goes to show that MPC is absolutely necessary, whatever approach is used for lifing the engine. This was agreed in the final discussion period by speakers from the US and Europe.

The extreme significance of motivation of all personel involved in the production of gasturbines, from the project team through NDI, process engineering, shop floor mechanics to supervisors, was stressed. Motivation can be promoted by, for example, training courses on the technical problems involved and by impressing on everybody the importance of the work he or she is doing.

2.4 Quality Assurance and Design Systems - L. Caroni and E. Campo, FiatAvio, Italy

FiatAvio demonstrates turbine disc life on the basis of crack propagation. Therefore preflawed discs are cyclically spin pit tested to failure. The initial flaw size to be introduced in the disc is determined by SEM inspection of the material in question and is of the order of a remote probability. One reason for the adoption of this lifing approach is the extremely large scatter of crack initiation life of turbine disc materials, expecially PM alloys, which would result in very low allowable stresses if the "safe life" approach were used.

2.5 Common Agard Approaches and Actions - Labourdette, Onera, France

This was more or less a discussion period on several subjects, for example:

- The usefullness of an Agard-Database on defect distribution was doubted by several discussions. Conclusion: Data bases are a long way down the line.
- Process Control Validation was missing as a topic in the four workshops. Conclusion: Agreed.
- Have the USAF gone back from RFC, do they have MPC at all?
  Answer: No to the first question, it is used in certain engines; yes to the second question, but the US do not place so much emphasis on MPC as some European manufacturers.
- Effect of defects, i.e. does a defect behave like a crack?
  Conclusion: That would be a good topic for the Agard SMP.
- Does automated NDI, as used in the USA have a high reject rate?
  Answer: In one case, 260 parts of 8000 were rejected, an acceptable rate.

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14. Abstract

The Structures and Materials Panel has organized a series of four Workshops planned within the framework of a Review on Damage Tolerance for Engine Structures. The Review aimed to address the areas critical to the acceptance of an approach based on damage tolerance concepts as an alternative lifeing philosophy to that of "safe life" for the design of engine components.

This publication is the last in the series on the Workshops. Previous topics covered by the Review include: "Non-Destructive Evaluation of Components", "Defects and Quantitative Materials Behaviour" and "Component Behaviour and Life Management", published as R-768, R-769 and R-770, respectively. This workshop addressed the need for, and the approaches to, ensuring component reliability and quality assurance. It surveyed the current procedures for materials and component specifications, standard process control, quality assurance and design systems. The prospects for devising a common NATO data base on integrity-related problems were examined.

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